Analysis of Queuing Delay in RPR Networks

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Abstract:

Resilient Packet Ring (RPR) that has been standardized as IEEE 802.17 is a MAC layer protocol designed for data centric metropolitan area network applications. A well-designed RPR network would be able to offer QoS guarantee for throughput and delay sensitive data classes in addition to providing other types of low cost best effort services. Careful network planning would be required to allow successful provisioning of classA services with strict delay and jitter requirements over RPR networks. This would require the knowledge of the dependency of delay and jitter for classA traffic on the load that is added to the ring. In this article, we propose an algorithm to estimate the dependency of delay and jitter for classA traffic in RPR networks on the total traffic added to the ring by nodes. We will follow an analytical approach based on queuing theory to find the probability density function of the delay for classA packets and try to find a closed-form solution to the problem using some simplifying assumptions. Simulations are used to verify the results of analytical derivations.

1. INTRODUCTION

The rapid expansion of data traffic demand has expedited the development of new technologies that allow faster and more efficient transport of data centric traffics over metro networks. Resilient Packet Ring (RPR) standard (IEEE 802.17) has been developed to address this requirement [1]. Service providers can use RPR to provide new types of data services over their metro networks while maintaining traditional carrier-class features such as resiliency and QoS. One of the important features of RPR is the ability to provide different classes of services ranging from high quality delay/jitter/rate controlled services (classA) to low quality best effort services (classC). RPR nodes have to apply strict classification and scheduling techniques to guarantee different service levels required by customers. Several separate queues are used in each node for different classes of service and each queue is treated differently depending on the requirement of each class. The highest priority for packet transport is given to the Primary Transit Queue (PTQ) that carries classA traffic transiting through each node. This is followed by the classA traffic added in each node. Other types of traffic (classB and classC) have lower priority. However, RPR nodes use a non-preemptive queuing mechanism where a low priority packet that is being processed in a node has to finish before a higher priority one can be serviced. This affects the delay and jitter of classA packets in the ring. Therefore, RPR priority based queuing mechanism cannot guarantee the carrier class traffic transport unless the capacity of the network and client data rates is wisely planned to guarantee the service requirements of classA traffic. In this article, we propose an algorithm to estimate the impact of the load added in an RPR ring on the delay and jitter of its classA traffic. We use an analytical approach and model the RPR queuing mechanism in the form of a queuing theory problem. We find a closed-form solution to the problem using some simplifying assumptions. The result can then be used as a rule of thumb for network planners to estimate the amount of delay and jitter for classA traffic based on the ring load and capacity.

Queuing theory has been used to analyze the traffic delay in SRP rings with one transit buffer [2],[3] and in RPR systems with more complex buffering mechanism [4]. A simplifying assumption that has been used in this analysis is that the traffic arrival in all the queues is a Poisson process. In this article, a realistic model of an RPR node and the network traffic is used and the complete analysis based on queuing theory is provided. An RPR simulation environment closely following the details of the standard has also been used to verify the analytical results. The analysis demonstrates the timing behavior of the traffic in RPR nodes and its statistical distribution. It is shown that the distribution does not follow the Poisson distribution model and an appropriate model for delay analysis is derived. We have also proposed a way to estimate the probability density function of the delay.

Section 2 of this paper introduces the basics of RPR classes of service and the queues deployed to implement them. Section 3 introduces the delay concept in RPR networks. Section 4 will include the analysis to derive the average queuing delay for classA packets in RPR networks; this implies the description of RPR queuing mechanism in the form of a queuing theory problem and finding a solution to this problem. In section 5, a solution will be proposed to find the distribution of queuing delay for classA packets in RPR networks, and finally section 6 will cover the summery and conclusion.

2. RPR Classes of Service

RPR network consists of dual counter-rotating rings both carrying working traffic. The transport ring acts as a shared resource and the task of controlling access of the nodes to this shared media is performed by the MAC layer. RPR MAC supports three different types of services:

- ClassA: This service is used for applications such as voice and video that require bandwidth guarantee and tightly bounded delay and jitter specifications.
- ClassB: This service provides guarantees for rate. However, it is used for applications that require less stringent delay/jitter requirements. Any usage above CIR (Committed Information Rate) is considered as EIR (Excess Information Rate) and will be treated the same as classC traffic
- ClassC: This class provides a best-effort service for data traffic that has no reserved bandwidth.

The RPR MAC on a station needs to process both ingress traffic being added by the MAC client for transmission on the ring and the transit traffic coming from the upstream neighbors on the ring destined for some downstream node on the ring. According to IEEE 802.17 standard, RPR MAC can optionally supports one of the two suggested transit path implementations: a single buffer implementation that places all classes of packets in one transit queue and a dual buffer implementation that uses two transit queues, primary transit queue (PTQ) for classA traffic, and secondary transit queue (STQ) for classB and classC traffic. In the following discussions, we will consider dual queue mode MAC that offers a better QoS guarantee.

The internal RPR queues architecture and their priorities are illustrated in Figure 1. In normal condition with no congestion or buffer overflow, PTQ packets have the highest priority. The next three priority groups are classA add traffic, classB add traffic and classC add traffic that all come from the client side and finally STQ packets have the lowest priority.

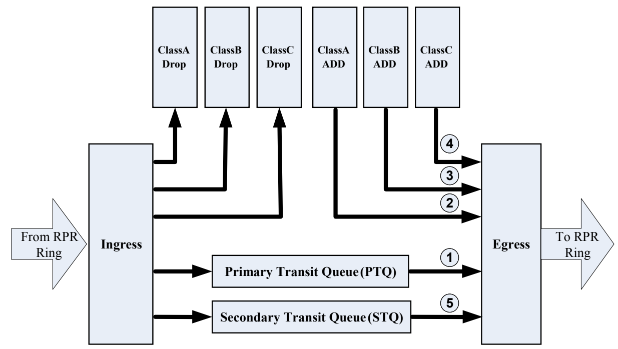

Figure 1. RPR MAC queues and their priorities

3. RPR Delay Concept

End-to-end delay for a packet is defined to be the time interval between the arrival of the packet at the transmit buffer of the source and the time when the packet is completely delivered to the next protocol layer of the destination node. Each packet spends some time waiting in queues on its way from source to destination.

In an RPR network, each packet is normally added to the ring by a node and forwarded by the other nodes to its final destination. A classA packet is queued in the PTQ of a transit node where it receives the highest transmit priority while other transit packets (classB and classC) are queued in the STQ of a transit node. Therefore, each packet experiences two types of queuing delay on its way from source to destination:

AddDelay: The interval between the arrival of a packet at the MAC transmit buffer of the source node and the time when that packet starts to be transmitted.

TransitDelay: The interval between the arrival of a packet at the MAC transit buffer and the time when the packet starts to leave that queue.

A packet passes some links on its way and this introduces the intrinsic link propagation delays to the total delay experienced by the packet. The packet also experiences a service time at each transit node due to the store and forward feature of the nodes. These add other terms to the total packet delay. The service time for a packet of length L bits in a channel with rate C bit/sec can be expressed by:

$$x = L / C \tag{1}$$

Moreover, the total end-to-end delay (D_{E2E}) for a packet that has passed H hops between its source and destination is given by:

$$D_{E2E} = H(T_S + T_{PD}) + D_A + D_T(H-1) \quad (2)$$

Where T_S is the service time, T_{PD} is a single link propagation delay, D_A is the amount of AddDelay, and D_T is per hop TransitDelay. According to equation (2) , end-to-end delay of a packet can be considered as the sum of three factors. The first two terms are propagation delay and service time that are constant for a packet of specified size. However, the third term, which is the delay factor due to waiting times in the queues of the network elements, is a variable term that is affected by several parameters. Noting the importance of providing controlled delay and jitter values to classA packets, we have to ensure a proper value for end-to-end delay and its variation.

We are interested in the average value of this delay to find the typical amount of latency in packet transmission. The probability density function of this delay provides more information that can be used to estimate the jitter induced by the packet transit. Therefore, our analysis is divided into two parts; in the first part, we will follow an analytical approach to find the average value of the queuing delay for classA traffic and in the second part, we will try to find the probability density function of the queuing delay. To perform such analysis, we first have to model RPR queuing mechanism in the form of a queuing theory problem.

As described before, the RPR queuing mechanism can be modeled as a fixed priority queuing system where customers stand in queues according to their priority groups. Customers belong to five different priority classes indexed by p (p=1, 2, 3, 4, 5) where p=5 represents the highest priority class. The system has one server that forwards the packet towards the Egress port. The system does not stop servicing a low priority packet upon arrival of a higher priority one and therefore, the queuing system is considered non-preemptive. For a priority queuing system where customers from priority group p arrive in a Poisson stream with rate λ_P customers per second, the average waiting time for class p customers can be calculated from equations (3)-(5).

$$W_p = \frac{W_0}{(1-\sigma_p)(1-\sigma_{p+1})} \qquad P=1, 2,.. 5 \quad (3)$$

Where:

$$\sigma_p = \sum_{i=p}^{5} \rho_i \quad (4)$$

$$W_0 = \sum_{i=1}^{5} \rho_i \frac{\overline{x_i^2}}{2\overline{x_i}} \quad (5)$$

Here, ρ_i is defined to be $\lambda_i \overline{x_i}$ and x_i is a random variable representing service time for class i packets [5][6].

In the case of an RPR queuing mechanism, the service time depends on the link capacities and packet sizes. Assuming an output rate of C, the service time distribution for all classes of packets is:

$$B_p(x) = f(xC) \qquad P = 1, 2... 5 \quad (6)$$

Where f(x) is defined to be the distribution of the packets sizes. In the following two sections, we will use this model to find the average value and distribution of classA packets in a typical situation.

4. The Average Value of Add and Transit Delay

In this section, we propose a method to find the average value of add and transit queuing delay for classA packets in a typical RPR ring that consists of N nodes all generating classA, classB, and classC traffic.

The following assumptions have been made in the analysis [7]:

- For all traffic classes, the arrival process of host packets is Poisson with the same mean arrival rate for all nodes. The Poisson distribution parameters are λ_A, λ_B and λ_C for classA, classB, and classC packets.

If the connection loads are low and the node does not perform much queuing, it has been shown [8] that the traffic is long-range dependant and may have large variations called burstiness. However, as the load increases, the arrival process of packets in nodes queues becomes much more like Poisson due to the law of superposition of marked point processes. Queuing can also change the distribution of traffic away from Poisson, but in high-speed links, the traffic can get quite close to Poisson.

The traffic is assumed to be trimodal for all nodes where 60% of the packets are 88 bytes, 20% are 536 bytes and the remaining 20% are 1542 bytes. Therefore, the distribution of packet size is given by the following probability density function:

$$f(L) = 0.6\delta(L-88) + 0.2\delta(L-536) + 0.2\delta(L-1542) \quad (7)$$

The above assumption comes from the typical distribution of packets in the internet. Small 64 bytes packets are TCP acknowledgement segments and TCP control segments such as SYN, FIN, and RST packets. Many TCP implementations that do not implement Path MTU Discovery use 512 bytes as the default Maximum Segment Size (MSS) for non-local IP destinations and a Maximum Transmission Unit (MTU) size of 1518 bytes is the characteristic of Ethernet-attached hosts [9]. We have added 24 bytes of RPR overhead bytes to these values to find the final distribution. It should be noted that the rates of RPR control and fairness messages are quite small compared to the total rate of packets and they can be ignored in this analysis.

- The probability that each node sends traffic to any other node is equal for all nodes.

Considering the fact that each RPR router services a great number of individual host nodes, the above assumption seems to be acceptable. In the case of average queuing delay computation, we can generalize this assumption to the condition when the probability that each node sends traffic to the other nodes is not equal and this would only change the value of α_N in equation (9).

To find the average values of AddDelay and TransitDelay for classA packets, an analytical approach based on queuing theory is used. The RPR queuing system is generally modeled as a G/G/1 queuing system where the arrival rate of customers in the system and the system service rate both have general form distributions. Nevertheless, solving the problem in the general case of G/G/1 queuing system is computationally expensive and a closed form solution cannot be found in this case. Queuing theory proposes straightforward, closed form solutions in the case of M/M/1 and M/G/1 queuing systems; therefore, we consider the possibility of modeling RPR queuing mechanism in the form of an M/G/1 queuing system. To validate this assumption, we should verify that the arrival rate for all priority groups could be modeled with a Poisson distribution with a negligible amount of error.

Starting with the classA traffic that is added by each node to the ring, the rate of classA traffic generation was assumed Poisson for each node. ClassA packets are subject to delay that is introduced by shapers before entering the add queue. However, we can still assume that the arrival rate of class A packets in the add queue is Poisson due to the fact that there is always a reserved capacity for classA packets and therefore the number of packets that are subject to the delay of traffic shapers are very small. Therefore, the effects of shapers on add queue arrival process can assumed to be negligible.

The second class of packets that we consider is classA transit packets that enter PTQ. The addition rate for classA packets at each node is assumed to be a Poisson process with mean λ_A and the average number of transit buffers that each classA packet passes to reach its destination is α_N. If the arrival rate of classA packets into PTQ can be assumed as Poisson, its mean would be given by:

$$\lambda_5 = \alpha_N \lambda_A \tag{8}$$

Noting the previous assumptions, the value of α_N in an RPR ring with N nodes can be estimated by:

$$\alpha_N = \sum_{i=1}^{N-1} (i-1)\frac{1}{N-1} = \frac{N-2}{2} \tag{9}$$

It should be noted that classA packets have a small amount of delay and jitter; therefore, we can assume that the Poisson traffic distribution will not change upon transit from PTQ buffer.

We have also performed a typical simulation to check the validity of assuming Poisson traffic distribution for classA transit traffic. The simulation has been done in a ring of 17 nodes as shown in Figure 2. All the previous assumptions including the Poisson traffic distribution, trimodal packet size and nodes sending traffic to each other with the same probability, are implemented in this simulation. The capacities of the links are assumed to be all at OC-12 rate that is about 622 Mbps. The Poisson distribution parameters are assumed to be λ_A=4000, λ_B=4000 and λ_C =10000. Figure 3 illustrates the distribution of classA packets interarrival time at PTQ.

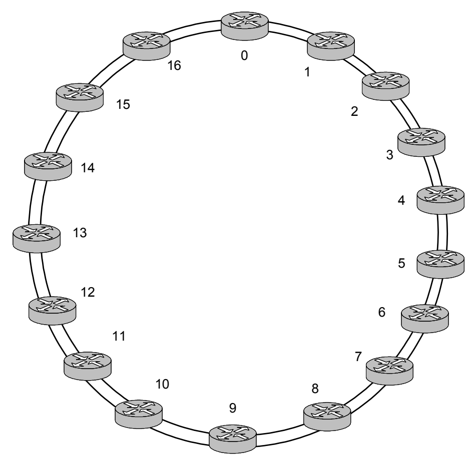

Figure 2. Simulation scenario of the RPR ring

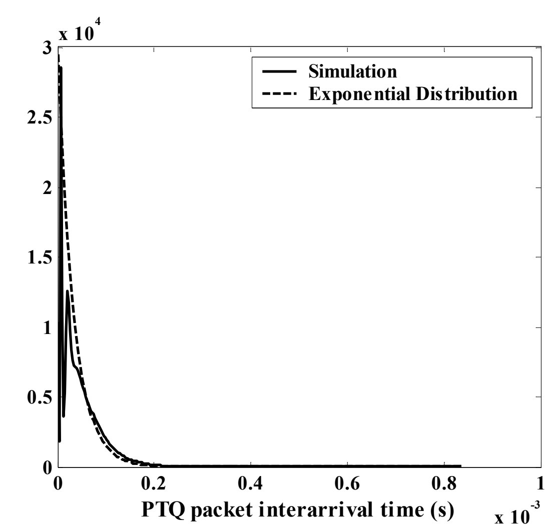

Figure 3. Packet interarrival time for classA packets entering PTQ

As can be seen in the figure, the interarrival time of the packets entering PTQ has a distribution that is a close match to an exponential distribution (dashed curve). The simulation also shows that the average interarrival time is about 0.33μs that is the same as what is derived from equations, showing a good match of the analytical modeling and the simulation environment.

Considering classB and classC packets that are added to the ring by each node, we can also neglect the traffic shapers effect and assume that the packet generation rates for these are also Poisson with distribution parameters specified by λ_B and λ_C respectively.

Packets in STQ have the lowest priority and their mean arrival rate is given by (10) if their arrival process can assumed to be Poisson:

$$\lambda_1 = \alpha_N (\lambda_B + \lambda_C) \tag{10}$$

Noting the lower priority of STQ, there could be considerable delay variations on the packets transiting this queue. These variations would add up during transit from each node. Therefore, the arrival process for classB and classC traffic may not be Poisson due to the considerable amount of jitter. We have performed another simulation to observe a typical distribution of classB and C traffic upon entering the transit queue. Same simulation parameters have been used in this case. Figure 4 shows the distribution of classB and classC packet interarrival time when entering STQ. As shown in the figure the distribution of interarrival time for these classes does not match the shape of an Exponential distribution.

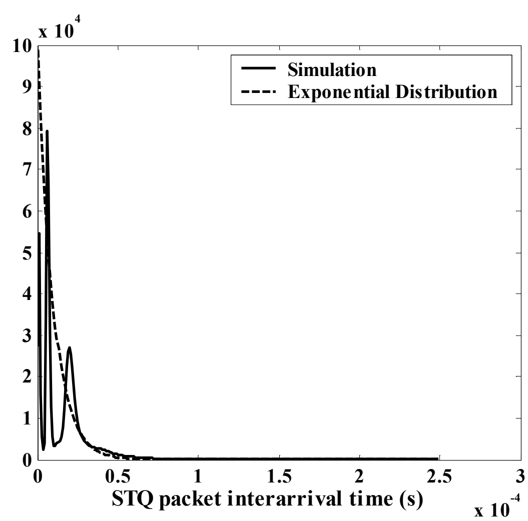

Figure 4. Packet interarrival time for STQ

Therefore, it is obvious that we cannot use a model of M/G/1 queuing system in general. Nevertheless, further analysis of the problem shows that there is still a way to use queuing theory and find answers with negligible amount of error.

The average delay that each priority group encounters depends on two factors, the first factor that is also the numerator of equation (3) is called the remaining service time. This is the time interval that a newly entered packet should wait for the queuing system to finish servicing the current customer being serviced and depends on the arrival process and service time for all priority groups. The second factor that effects the average delay time is the denominator of equation (3). This factor is the time interval when a packet should stand in queue waiting for the higher priority packets to be serviced. Therefore, for each priority group this depends on the groups that have equal or higher priority.

Our goal is to compute the average queuing delay for classA packets where it matters most. Therefore, if we become sure that the non-Poisson arrival processes of classB and classC packets do not affect the remaining service time, we can still use the M/G/1 queuing system relations although we know that classB and classC packets do not follow a Poisson distribution.

The result of calculating the remaining service time using these assumptions and applying equation (5) is approximately 6.68 μs. The simulation result for the remaining service time is shown in Figure 5 that is around 7μs. This again demonstrates the close match of the analytical modeling and simulation results.

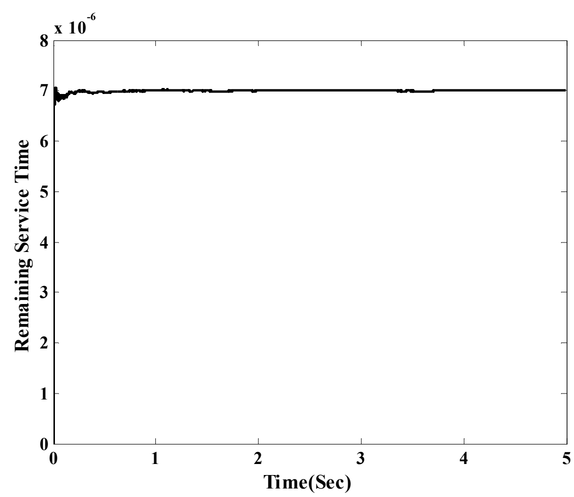

Figure 5. Remaining service time parameter for classA packets

Assuming that the arrival processes of classB and classC packets do not affect the remaining service time, we can now calculate the average delay for classA packets using equations (3)-(5) and the simulations show that these results are good approximations for the real values.

5. Approximation of the Distribution of Add and Transit Delay

Delay is not the only important parameter in the transport of classA packets, but the variations of delay known as jitter has also an important role in the QoS. Therefore, in this section we will propose a way to estimate the probability density function of delay for classA packets from which jitter can also be estimated.

For an M/G/1 queuing system, we can calculate the probability density function of queuing delay from (11).

$$W_p^*(s) = \frac{(1-\rho)[s+\lambda_H-\lambda_H G_H^*(s)]+\lambda_L[1-B_L^*(s+\lambda_H-\lambda_H G_H^*(s)]}{s-\lambda_p+\lambda_p B_P^*(s+\lambda_H-\lambda_H G_H^*(s)} \quad (11)$$

Where $W_p^*(s)$ is Laplace-Stieltjes transform of random variable W and other parameters are defined in (12)-(16):

$$\lambda_H = \sum_{i=p+1}^{N} \lambda_i \quad (12)$$

$$\lambda_L = \sum_{i=1}^{p-1} \lambda_i \quad (13)$$

$$B_L^*(s) = \sum_{i=1}^{p-1} \frac{\lambda_i}{\lambda_L} B_i^*(s) \quad (14)$$

$$B_H^*(s) = \sum_{i=p+1}^{N} \frac{\lambda_i}{\lambda_H} B_i^*(s) \quad (15)$$

$$G_H^*(s) = B_H^*(s+\lambda_H-\lambda_H G_H^*(s)) \quad (16)$$

Finally the pdf of the delay ($f_p(w_p)$) can be found using inverse Laplace-Stieltjes transform of $W_p^*(s)$ [10].

However, in the case of delay distribution of classA packets, the solution is not as straight forward as it seems. First, solving the nonlinear equation (11) in terms of parameter s is not so simple and no closed-form solution could be found. It should be solved once for each s to find all the points of $W_p^*(s)$ and then an inverse transform should be performed. Second, the M/G/1 assumption is not correct and we cannot follow the effect of non-Poisson distribution of classB and classC as in the previous case. Therefore, it seems that queuing theory cannot guide us to a direct analytical solution in finding the distribution of Add and TransitDelay for classA packets. In the previous section, we have derived an equation to find the average value for add and transit delay. Therefore, the only known parameter in the distribution is the first moment. In this stage, we have performed several simulations and observed the distribution of classA add and transit delay in different cases. We have changed the number of nodes and their traffic rates so that in all cases more than 80% of the ring capacity is used without severe congestion that affects the delay and jitter of the packets. In almost every situation, the overall characteristics of the distributions remained the same independent of the number of nodes and their traffic rates.

Figure 6 shows the probability distribution function (PDF) of AddDelay for classA packets and Figure 7 shows the PDF of per hop TransitDelay for classA packets for various number of ring nodes.

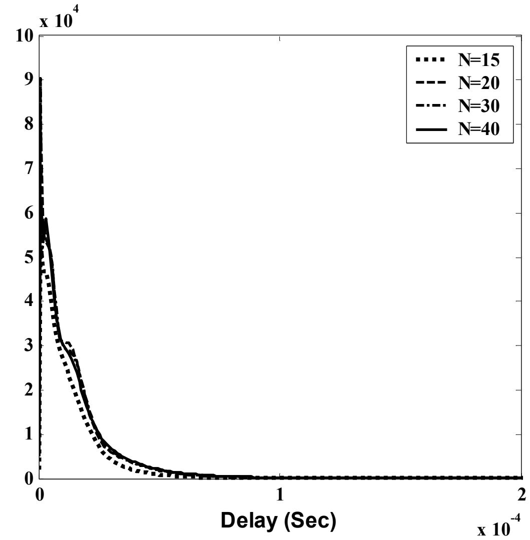

Figure 6. Distribution of ClassA AddDelay

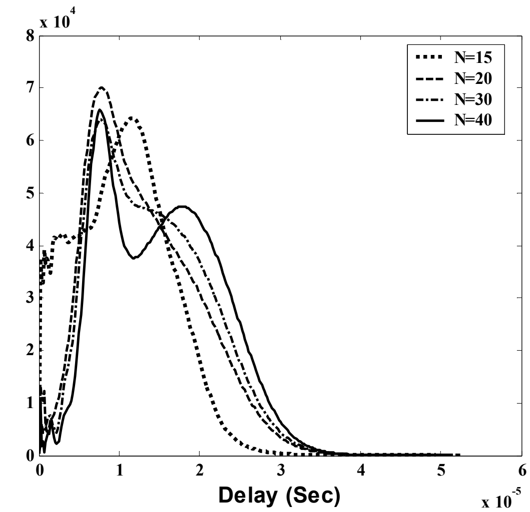

Figure 7. Distribution of ClassA TransitDelay

Considering the fact that the distributions all follow a similar shape, we have tried to find a standard distribution that best fits the simulation results. Fortunately, the probability density functions that we have found in the previous section have been found to be similar to some standard probability density functions. AddDelay distribution can be best approximated by an exponential distribution and Rayleigh is the best approximation for TransitDelay distribution. Figure 8 and Figure 9 show both the main distributions and the approximations together in one of the cases. It can be observed in the figures that the distribution of Add and Transit Delay closely follow the standard distributions.

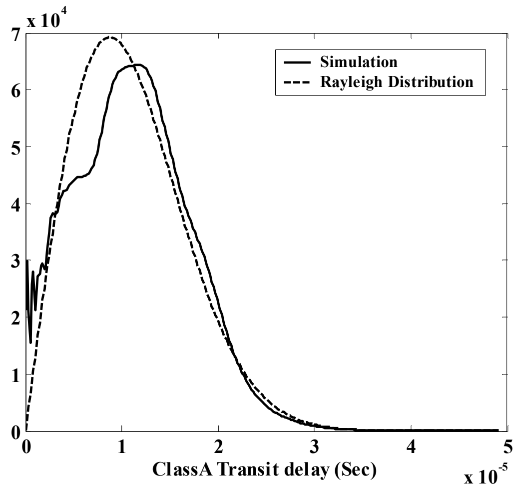

Figure 8. Main distribution and Rayleigh approximation for ClassA TransitDelay

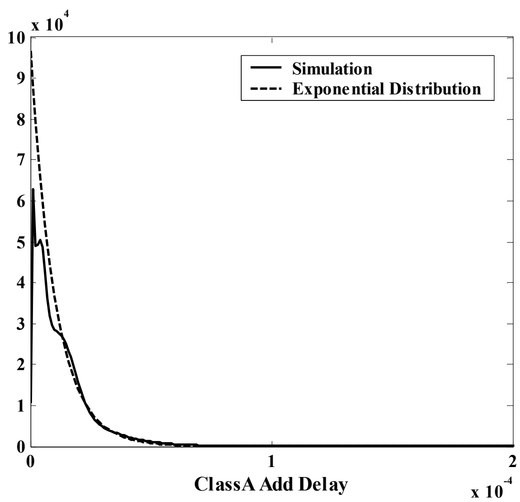

Figure 9. Main distribution and Exponential approximation for ClassA AddDelay

A comparison among the first, the second and the third moment values of the two distribution functions as shown in Table 1 and Table 2 also verifies a close match that could be concluded visually from the figures.

Table 1 The first three moments of Rayleigh distribution and simulation result

	Simulation	Rayleigh Distribution
First Moment	1.088×10^{-5}	1.098×10^{-5}
Second Moment	1.536×10^{-10}	1.534×10^{-10}
Third Moment	2.487×10^{-15}	2.526×10^{-15}

Table 2 The first three moments of Exponential distribution and simulation result

	Simulation	Exponential Distribution
First Moment	1.035×10^{-5}	1.035×10^{-5}
Second Moment	2.474×10^{-10}	2.155×10^{-10}
Third Moment	7.335×10^{-15}	6.649×10^{-15}

Therefore we can assume that the distribution for Add and Transit delays are exponential and Rayleigh respectively. Having this assumption the only remaining problem is to find the parameters of these distributions.
Assuming that a random variable x has a Rayleigh distribution with parameter b:

$$f(x)=\frac{x}{b^2}e^{\left(-x^2/b^2\right)}u(x) \tag{17}$$

Then:

$$\overline{x}=E(x)=\sqrt{\frac{\pi}{2}}\,b \tag{18}$$

Therefore, for a random variable x with Rayleigh distribution, $\overline{x}$ can give us all the information to find the probability density function of that random variable. Similarly, a random variable x with exponential distribution can be described by a single parameter:

$$f(x)=\frac{1}{\mu}e^{-x/\mu}\,u(x) \tag{19}$$

And

$$\overline{x}=\mu \tag{20}$$

Therefore it can be concluded that the single parameter of exponential and Rayleigh distributions may be found knowing the average value of the random variable. Estimation of the average value for Add and Transit delay has been discussed in the previous sections and a proper method has been introduced. Therefore, we can easily find the parameters of the distributions and thereby, specify their behavior.
We have found the value of b and μ for the described scenario from both simulation and equations (18) and (20) and the results are shown in Table 3. It can be seen that there is a close match between the results.

Table 3 Comparison between simulation and analytical results

Parameter	Derivation method	
	Simulation	Analytical
b	7×10^{-6}	6.5×10^{-6}
μ	10.16×10^{-6}	10.23×10^{-6}

6. Summary and Conclusion

In this paper, we have proposed a method to find the average value and the probability density function of the delay for classA packets in RPR networks. This proposed technique would be useful for network planners to realize the dependency of classA traffic delay and jitter on the total load imposed on the RPR ring.

We have modeled RPR queuing mechanism in the form of a queuing theory problem and solved this problem analytically to find the average value of the delay. We have also proposed a method to find the probability density function of the delay for classA packets and tried to find a closed-form solution to the problem using some simplifying assumptions. An accurate simulation model of RPR nodes has been developed and it has been used through all stages as a verification tool to verify the assumptions and results.

7. REFERENCES:

[1] IEEE, IEEE 802.17 standard, "Resilient packet ring (RPR) access method & physical layer specifications," 2004

[2] D. A. Schupke "Packet Transfer Delay of the SRP Ring," in *Proc. IEEE Conf. on Local Computer Networks LCN*, Nov 2001, pp. 464-465.

[3] D. A. Schupke, A. Riedl, "Packet Transfer Delay Comparison of a Store-and-Forward and a Cut -Through Resilient Packet Ring," in *Proc. Int'l Zurich Seminar on Broadband Communications*, *IZS,* Feb. 2002.

[4] S. Zhou, F. Ao, M. Chen, "Delay and Throughput Performance Analysis of RPR's Three Priorities Traffic," in *Proc. Int'l Conf. on Communications, Circuits and Systems, ICCCAS* , vol. 1, June 2004, pp:660 – 664.

[5] P. Nain, "Basic Elements of Queuing theory, Application to the Modeling of Computer Systems," Lecture Notes, Univ. Massachusetts, 1998.

[6] R.W. Conway, W.L. Maxwell and L.W. Miller, "Theory of Scheduling," Addison-Wesley, 1967.

[7] "Guidance for RPR 802.17 Performance simulations," IEEE 802.17 Working Group, Nov. 2001.

[8] J. Cao, W.S Cleveland, D. Lin and D.X Sun, "Internet Traffic tends to Poisson and Independence as the load Increases," Bell Labs, Murray Hills, NJ, Tech. Rep., 2001.

[9] K.C. Claffy, G.J Miller and K. Thompson, "The Nature of the beast: Recent traffic Measurements from an internet Backbone," in *Proc INET '98*, July 1998.

[10] L. Kleinrock "Queuing Systems, Volume II: Computer Applications," New York, John Wiley & Sons, 1976