Modeling and Analysis of High Speed Parallel Token Ring Networks

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Abstract

Communication performance like computer performance is affected by parallelization. In this paper, we identify four factors in parallel token ring systems which can improve network performance. Further, we develop an analytical model to predict the performance of these systems. The performance predictions obtained with the analytical model are compared with simulation results. While the current model accurately predicts the performance of networks with sixteen or more rings, it is not so accurate at lower number of rings. The short/long cycle behavior of the token interarrival times are identified as one cause of the inaccuracies. Finally, we discuss the benefits and limitations of parallel token ring networks for gigabit speeds.

1 Introduction

The use of parallel communication channels to achieve a gigabit network is a very interesting concept. Especially, if a gigabit network needs to be built from existing systems such as the common carrier system, a network of parallel channels may be a viable alternate. However, its appropriateness can only be ascertained after determining its behavior under different load conditions. To this end, we have conducted analytical and simulation studies to define the factors in parallel token ring networks which can improve network performance.

Currently, several analytical models have been suggested for single channel network architectures such as token ring networks [2, 14], slotted ring networks [8], and insertion ring networks [3, 11]. However, very few models exist for parallel networks [1]. Almost all these studies attempt to capture the performance aspects of the networks but do not address the issue of identifying key factors that contribute to the improved performance. Some studies in multiple queue systems have identified the coalescing phenomenon in the presence of multiple servers [10, 13].

In this paper, we develop an analytical model to represent parallel token ring networks. Our aim is to find a model which can permit the study of the effects of the individual factors to be partially isolated so that particular features can be analyzed and their effects separated. The suitability of the model is tested through simulation of parallel token ring networks. We have experimented with both nonexhaustive and exhaustive service policies.

This paper is organized as follows. In Section 2, we identify four important factors that influence the performance of parallel token ring networks. An analytical model which isolates these factors is developed in Section 3. In Section 4, we present a summary of the results obtained from network simulations and compare these to the results obtained from the analytical model. Finally, Section 5 presents a summary of our approach and suggests further research to develop protocols with improved performance for parallel networks.

2 Factors Influencing Parallel Token Ring Network Performance

Four basic factors have the potential to improve network performance when parallel token ring networks are employed. The first of these is obviously increased bandwidth. This particular factor occurs even when parallel networks are maintained independent of each other, that is, where messages are submitted to each network separately or when a higher data rate communication system is used in a single network. The major factor in attaining performance improvement for independent (and parallel) networks is to
achieve some form of load balancing so that each message can be submitted to the network best capable of handling the traffic at the instant of time that the message is ready for transmittal. In the case of increased data rate on a single channel, the service time for each message is similarly reduced so that this factor can be handled by the normal analysis techniques for that type of access protocol.

A second factor which can improve parallel network performance is topology. Considerable work has focused on topology and routing in multi-channel networks [12, 15]. Here the performance studies are designed to limit the number of gateways or hops necessary to connect the nodes. Additional topology work is related to reliable communication paths in case of link or node failures. We have not considered bandwidth and topology and routing problems in this paper.

The other two factors that contribute to network performance improvements are based upon queueing theory analysis. They are the improvement provided:

- when the time between consecutive network accesses (i.e., time between token arrivals) is decreased due to the existence of multiple tokens for the message queue at a node; and

- when statistical parameters (e.g., variance of token interarrival times in a token ring network) in the server's distribution function are decreased leading to an attendant decrease in wait time.

These two factors are the ones which are primarily studied in this paper. With multiple tokens, it is possible for the service to start more quickly. This can still result in an advantage even if the service takes more time because of any reduced bandwidth (e.g., if the total bandwidth of a communication system is kept constant, then increasing the number of parallel networks decreases the bandwidth of each network). Work related to performance improvement provided by decreasing the token interarrival times in multiple token rings are studied by Bhuyan et al [1] and Morris and Wang [13]. In both studies, bandwidth is also increased (with the increase in number of rings) so that it is difficult to separate the effects of bandwidth and interarrival related issues and more specifically, the conditions under which improvement can take place.

In the next section, we will investigate the effect of these two factors on service time and waiting time in a parallel token ring system.

3 Analytical Model for Parallel Token Ring Networks

Most models of token ring networks have concentrated on the wait time effects of queueing. Both approximate [4, 14] and exact [16] analytical models have been developed. Our approach to an analytical model is not to improve on this work but to provide a model which can support the separation of the influence of token interarrival time (which affects mean service time) and the variation in interarrival time (which can additionally affect the wait time in the queue).

Generally token rings are identified by the service discipline at a node when a token is received. With an exhaustive service discipline, a token is retained at a node until its queue is empty. With a nonexhaustive service discipline, a node can transmit only one message each time it captures a token. Even though there are a number of other variations of these two basic protocols (e.g., gated service [16]), in this paper we limit our study to the above two service disciplines.

3.1 Service Time Considerations

3.1.1 Nonexhaustive Service Discipline

We define the service time, $S$, for a nonexhaustive service discipline as a combination of the time for the message at the head of the queue to wait for the token (also referred to as residual token time), $T_r$, followed by the placement time (i.e., transmission time) for the message, $z$. The wait time, $W$, is the time a message waits in a queue before it becomes the head of the queue. The mean service time is given by:

$$ S = T_r + z $$(1)

Similarly, the mean wait time may be derived using the Pollaczek-Khinchin formula (e.g., [7]):

$$ W = \frac{\lambda S^2}{2(1 - \lambda S)} $$ (2)

where $\lambda$ is the rate of arrival of messages at any node in the system.

The reason we have selected this queueing model format is that it successfully separates the effects of residual token time. Here, the service time is directly related to the mean residual token time (Equation (1)). Similarly, wait time is a function of both message arrival time and the second moment of service time. However, assuming statistical independence

$$ S^2 = T_r^2 + 2zT_r + z^2 $$ (3)
If message lengths are fixed then \( W \) is a function of the first and second moments of the residual token time. These affects are easily separated by knowing or estimating the mean service time. Thus, we can use this model to study the effects that token arrival time has on both service and wait time and can separate the service time variations by considering \( T_r^2 = T_r^2 + \sigma_k^2 \) where \( \sigma_k^2 \) is the variance of the residual token time.

### 3.1.2 Exhaustive Service Discipline

In this case, all messages which arrive during the period when a token exists at a node are serviced immediately instead of waiting for a new token to arrive. If we refer to the time during which a token was held by a node as a busy period, then the service time analysis could be based upon busy cycles. A busy period is defined as the time between the arrival of a message to the head of a queue at a node to the time the token that transmits this message leaves the node [5, 6]. The service time for the busy period (which is not the same as message service time) consists of residual token time and the time necessary to exhaust all the messages in the queue. We can now express the mean service time \( \overline{S} \) for a busy period in terms of the residual token time \( (k) \), the transmission time \( (a) \), and the number of messages transmitted during a busy period \( (k) \).

\[
\overline{S} = T_r + k \overline{a}
\]  

Similarly,

\[
\overline{S^2} = T_r^2 + k^2 \overline{a^2} + 2k \overline{a} T_r
\]  

Note that in the exhaustive case, service time, \( \overline{S} \), for the busy period is actually service for the busy cycle. Hence, wait time based upon Equation (2) is actually the message occupation time, that is, the time that a message must wait while the server is occupied with prior messages [7].

### 3.2 Interarrival Time Considerations

As noted in Section 3.1, in order to obtain the service time we need the time at which the token arrives after a message has arrived at the head of the queue. This time is given by the concept of residual life. An excellent discussion of residual life based upon renewal theory can be found in [9]. The moments of the residual life are given by:

\[
\overline{T_r^n} = \frac{I_{n+1}}{(n + 1) I_1}
\]  

where \( I_n = (t_k - t_{k-1})^n \), and \( t_k - t_{k-1} \) is the interarrival time between tokens.

One of the distinct features of residual life is that it is more likely for an arrival event, in this case, a message arriving at a node, to occur during a long interval than over a short interval. This factor is extremely important in the parallel ring system because token arrival opportunities occur considerably more rapidly and possibly with more variation than in a single ring. As a result it is very important to understand and model precisely the characteristics of token interarrival times for parallel networks.

### 3.3 Token Rotation Time Considerations

Previous authors [10, 13] have noted that when multiple servers were used in a token ring system there is a tendency for the servers to move together from queue to queue. In some systems this tendency can be alleviated by randomizing the visit cycle to create dispersive schedules. However, in many networks, service schedules must follow the physical ring structure. Hence, alternative dispersive schedules are not feasible without physically reconnecting the network. We have studied this correlation phenomena in greater detail in this paper.

Tokens tend to group because of the relation between message and token arrivals. A token in the lead is much more likely to encounter a node with a message because the upcoming nodes have waited for the tokens to progress around the complete network. The following tokens pass through nodes who have had little time to accumulate a message since the previous arrival. When the lead token stops to service the message, the following tokens tend to pass it and a new token now leads. The new lead token is now most likely to encounter a message. Thus, the lead token in a group is much more likely to service a message than the other tokens within the group. This is precisely the type of operation which is described in residual analysis as noted from the discussion Section 3.1.

A basic structure which illustrates the token grouping is to plot the histogram of token interarrival times. A typical sketch is shown in Figure 1. Here there are two distinct arrival conditions occurring: those caused by the tokens rotating as group around the ring and those caused by the group of tokens as they are dispersed due to the lead token being stopped for a message and the remaining tokens catching up and passing it. The percentage of each arrival group is governed strictly by the number of rings. For example if there are two rings then 1 arrival will be within the group and 1 arrival for the group as it progresses around
the ring. Thus, the curves will each have 50% of the area. For four rings, 75% of the interarrivals will be within the group and 25% will be for the group rotation around the ring.

This feature can readily be described by an equation of the form:

\[ p(l) = \beta \cdot p_g(l) + (1 - \beta) p_l(l) \]  

where \( \beta \) is the fraction of time over which the group behavior is observed; \( p_g(l) \) is the group interarrivals; and \( p_l(l) \) is the ring interarrivals.

One can readily see from Figure 1 that the first, second, and third moments of the interarrival times needed to calculate the residual token time will significantly favor the ring arrival segment unless the segment strength, \( \beta \), is very large, that is, the number of parallel rings is large.

4 Results

The results obtained in this study, through analysis and simulation, are summarized in this section.

4.1 Parallel Token Ring Network Model Results

As noted previously, one of our research objectives is to develop a model which is capable of predicting the performance of parallel communication systems. In this task, a simulation system was implemented to collect a number of related statistical variables which could be used in examining the service and wait times derived from the model developed in Section 3.

Since we are mainly interested in measuring the effect of token interarrival times, we have considered fixed length packets (\( s = 10 \) Kbits), thereby eliminating the effect of variations in transmission times. Since we are interested in determining the effects of parallel tokens on the network performance, we consider a single token ring network with nonexhaustive service discipline as a base case. For this reason, we express the network load in terms of the traffic intensity (\( \rho \)) at each node in a single token ring system which is given as [1, 14]

\[ \rho = \frac{M \lambda r}{1 - M \lambda s/B} \]  

where \( M \) is the number of nodes on the ring, \( \lambda \) is the rate of arrival of messages at each node, and \( r \) is the time to pass a token between two adjacent nodes. In this paper, we present results with three load factors \( \rho = 0.1, 0.5, 1.0 \)\(^1\). By definition, loads with \( \rho > 1.0 \) are not valid for single token rings. However, such loads can be valid for multiple rings. We considered networks with a total bandwidth of \( B = 1 \) Gbits/sec, with \( N = 1, 2, 4, 8, 16, 32 \) rings, \( M = 50 \) nodes, and \( r = 1/150 \) msec. Thus for a given \( \rho \), the rate of arrival of messages at a given node is given by \( \lambda = \rho/(1/3 + 0.5 \rho) \) per millisecond.

4.1.1 Nonexhaustive Service Discipline

First, we consider the nonexhaustive policy. Here, the mean service time \( \bar{S} \) may be estimated based on observed token interval times, \( I \) and \( I^2 \), and message transmission time, \( x \), using Equations (1) and (6). Similarly the \( S^2 \) may be estimated using Equations (3) and (6). The observed and the estimated values of \( \bar{S} \) and \( S^2 \) are summarized in Figure 2. \(^2\)

Figures 2a & 2b compare the estimated values of service times with the values obtained through simulation. From here, it may be observed that:

- The estimates of \( \bar{S} \) for single ring networks are not accurate. In fact, this discrepancy between the values obtained through simulation and analysis increases with the load. For example, when the load factor is 0.1, the analysis overestimates the mean service time by 25%. With a load factor of 0.50, the underestimation is as much as 50%. Load factors of \( \rho \geq 1.0 \) saturate the single ring and hence are not considered by the analysis.

- At moderate loads, the estimates of \( \bar{S} \) are reasonably accurate with multiple rings. When the load factor is 0.5, the percentage deviation of estimates from the simulated are within 6% for 4 rings, and within 2% for other multiple ring networks. The accuracy of estimations seem to vary with the load, but it is not very significant.

- For single ring networks, the above observations for \( \bar{S} \) are also relevant for \( S^2 \). At the low load factor of 0.1, the analysis underestimates it by 30% and at high load factor of 0.5, the underestimation is 70%.

- For multiple rings, the analysis is able to estimate \( S^2 \) more accurately than \( \bar{S} \). The estimates are most accurate when load factor is 0.5. In general, the accuracy is highest for 32 rings networks.

\(^1\)Alternatively, we could have expressed the load as \( \lambda = \rho/(M \rho + \rho M s/B) \).

\(^2\)In Figures 2-5, the response time, the service time, the wait time, and the token interarrival time are expressed in milliseconds.
The wait times ($\bar{W}$) may be estimated based on the observed token interarrival times $I_1, I_2$ and $I_3$ (Equations (1)-(3), (6)). They may also be estimated using the observed values of the service time moments (Equation (2)). Figure 2c summarizes the wait times obtained through analysis and compares them with the values from simulations. We consider two estimates for wait times. $A1$ is based on Equation (2) using observed values of $S$ and $S^2$. $A2$ is based on the estimated values of $S$ and $S^2$ (using the first three moments of the token interarrival times). It may be observed that:

- For a single ring, $A1$ (computed from observed service times) is always lower than the observed values. This matches with the observations related to the service times. There is a small discrepancy at low loads (e.g., 0% at 0.1) and high discrepancy at high loads (e.g., 50% at 0.5).

- In the case of multiple rings, the deviations in estimations are small. However neither of the two estimators appears to be a close approximation in all the cases. For example, for a two ring configuration, $A2$ is the best estimator over all the loads (discrepancy is 0% at 0.1 and 8% at 1.00). With eight rings, $A1$ is appropriate at low loads. Surprisingly, at $\rho = 1.0$, the estimations for 4 and 8 rings deviate drastically from the observed waiting times.

- For 32 rings, at all reasonable loads $A1$ and $A2$ are almost the same. At $\rho = 1.0$ there is a maximum difference of 10% in the two estimates.

As noted in Sections 1 and 2, two factors which influence performance exist within the wait time structure, i.e., $S$ and $S^2$ of Equation (2). In addition,

$$S^2 = S^2 + \sigma^2_S$$

Thus, it is desirable for best performance not only to reduce $S$ but also to reduce the variance $\sigma^2_S$. When $S^2$ is approximated as $S^2$, the resulting estimate of $\bar{W}$ is found to be quite close to the observed values of $\bar{W}$.

4.1.2 Exhaustive Service Discipline

In this case, the mean service time can be estimated using Equations (4) and (6). Here, in addition to the token interarrival times, we also need $k z$. In the case of $S^2$, we use Equation (5) for estimation. In order to separate the effects of $k$ and $z$, we considered constant length packets in simulation. Hence, $k z = z k$ and $k z^2 = z^2 k^2$. The parameters for simulation are the same as the ones for the nonexhaustive policy. The results are summarized in Figure 3. From here, it may be observed that:

- The accuracy of the estimates for both $S$ and $S^2$ improves with the increase in number of rings. For 32-ring networks, the estimates for $S$ are within 6% at 0.1 load and 4% at 1.0. The analysis seems to estimate $S^2$ more accurately than the first moment. For both 16 and 32 rings, the analysis can estimate $S^2$ within 2% of the values from simulation.

- For 1-ring to 16-ring networks, the service time improves with the number of rings. Beyond 16 rings, the service time becomes worse with the increase in rings.

- The accuracy of the estimates with exhaustive policy seem to be higher than those with nonexhaustive policy.

4.1.3 Token Rotation Time Considerations

As discussed in Section 3.3, the tokens in a multiple token ring are not always equally spaced in the ring. As a consequence, there are long inter-token intervals $I$ and short inter-arrival times (with respect to any node). In this paper, we only analyze the behavior of the tokens with the nonexhaustive policy.

From our simulation experiments with the 2-ring networks, we make the following observations.

- At all loads, $I$ is within the 0.0-0.1 msec range 50% of the time. This corresponds to the short cycle. For $\rho = 0.1$, it is in the 0.3-0.6 msec range for 49% of the time. This corresponds to the long cycle.

- As the load factor is increased, the behavior of the short cycle remains the same (i.e., 0.1-0.2 msec with 50%), but the duration of the long cycle becomes longer. For example, when $\rho = 0.1$, $I > 0.6$ for only 1% of the time. At $\rho = 1.0$, however, $I > 0.6$ for 42% of the time.

- In spite of the fact that the average value (7) is increasing with the load, the fraction of time during which $I$ is in the short cycle remains the same (50%). This is not obvious from the description of the multiple ring protocol.

From the above observations at analysis and simulation results, we make the following conclusions regarding the applicability of the model.
The analytical model developed in Section 3 accurately predicts the performance of ring networks with 16 or more rings. The prediction is accurate at all network loads. Similarly, it is accurate with both exhaustive and nonexhaustive service disciplines.

For other lower ring structures, the model is accurate at low and moderate loads. But it is not accurate at very high loads \( \rho = 1.0 \). This may be attributed to network saturation in token rings in these configurations.

The accuracy of wait time estimations is enhanced when the variations in the service time are ignored and \( S^2 \) is approximated as \( S^2 \).

The token interarrival times display short cycle and long cycle behavior for structures of one to 8 rings. The length of the long cycle is higher at higher loads.

From here, we conclude that our analytical model is quite accurate for structures with 16 or more rings. In addition, by incorporating the short and long cycle behavior of the token interarrivals \( I \) into the model, we predict that this model can also be used for lower ring structures. We are currently working on these extensions.

4.2 Parallel Token Ring Network Performance Factors

In Section 2, we presented two factors by which parallel computer performance could be improved. The first of these relates to the improvement in access time as a result of parallel systems. In a token ring system, it is related to the improvement in token arrival as the number of rings is increased, that is, it is directly related to the residual token arrival time. In the model and the simulation studies this factor is directly correlated to the service time. From our results, we make the following observations.

- Figures 2 and 3 compare the service times for a multi-channel token ring. It may be noted that up to 16 rings the service time is consistently reduced by increasing the number of rings. Beyond 16 rings, however, the service time increases with the number of rings. This can be explained with the help of Equations (1) and (4). With the increase in number of rings, the transmission time per packet \( z \) is increased. However, due to the presence of multiple tokens, \( T_T \) is decreased.

Thus, for the given network parameters, the gains due to reduced token interarrival times do not compensate for the increased transmission times beyond 16 rings.

Our simulation results are indicative that the multiple tokens tend to group affecting both the service and the wait times of the system. Currently, we are further investigating this behavior.

- Figure 4 summarizes the response times for different ring structures and different load factors. Message response time \( R_t \) is defined as the time a message has arrived to a node to the time it has reached its destination.

Networks with exhaustive policy have a different response time behavior. As observed before, the gains due to multiple rings are lost beyond 16 rings. Accordingly, the response times for 32 rings are larger than for 16 rings. Similarly, the reductions in response times are not as drastic as in the nonexhaustive case. The gains due to 2 and 4 rings are almost negligible. With 8 rings and above, however, there is a substantial reduction in response times. Similar conclusions may be drawn regarding the variance.

- The observations regarding the token interarrival times are summarized in Figure 5 which presents the mean and variance of the token interarrival times \( (I, \sigma_I^2) \) at any given node in the network. A token arrival is included irrespective of its usage for transmitting a message on arrival at a node. It may be observed that \( I \) increases linearly with \( \rho \). As the number of rings is increased, \( I \) is decreased. \( I \) seems to be inversely proportional to the number of rings.

The observations for the mean interarrival times do not seem to fit the observations for the variance. Among the multiple ring networks, the variance is high for 2 rings and is low for 32 rings. In the case of exhaustive policy, the variance for 2 rings is even higher than the single ring. The high variances for low ring count is presumably due to the grouping phenomenon discussed earlier.

In summary, it has been found that multiple rings with a given total bandwidth are much more efficient.
than a single ring with the same bandwidth. The gains are achieved due to the availability of multiple tokens, due to the decrease in variance of the service and wait times, and the reduction of long cycles in token interarrival times. These are in addition to the more obvious benefits such as increased reliability, allocation of rings based on diversity of applications, etc.

5 Conclusions

The analysis and simulations have shown that parallel networks can provide significant performance improvements for high data rate communications systems. Many factors are involved in this performance improvement including individual and total bandwidth, network count, network length and service policy considerations. However, the results have shown that performance improvements can be significant even when individual network bandwidth is a fraction of the total bandwidth provided by the parallel network. In fact, the simulation results have shown that improvements of an order of magnitude or better can occur for parallel networks with identical total bandwidth. In addition to response time improvements, parallel networking provides a significantly broader range of service policies which may be utilized effectively. Further improvements appear to be available through selective and/or more complex service policies.

In the future, we plan to investigate further token and other parallel ring structures in order to improve parallel performance models and to document parallel network systems as a mechanism for providing high data rate communications.

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References

Figure 1. The Probability Density Function of the Token Inter-Arrivals

Figure 2a.

Figure 2b.

Figure 2c.

Figure 2. Service times and Wait times with varying load factors
Figure 3. Service times with varying load factors (Exhaustive service)

Figure 4. Response Times with varying load factors
Figure 5. Token Inter-arrival times for varying load factors