Dynamics of Token Ring Protocols

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Abstract

In this paper we present a new approach for analyzing token ring LANs. The token ring model presented supports the behavior obtained from actual ring measurements. Using this model, employing deterministic bounds analysis techniques, we prove several theorems which lead to some interesting conclusions that support observed ring performance. The results obtained give insight into practical behavior of a token ring environments.

1 Introduction

Local area communication networks (LANS) have proliferated during the past decade [5,9,13,14,17,11]. Because of their widespread use, because they are found supporting numerous higher layer protocols, and because of the diversity of applications that can be found using them, interest continues to grow in understanding their performance [3,8,10]. Current understanding of the performance behavior of LAN environments is not adequate. Little insight and practical performance management information is available [7,15,16,18].

This paper presents a deterministic analytic model of the IEEE 802.5 LAN standard as well as extensions made by some 16 Mb implementations and Fiber Distributed Data Interface (FDDI) [12,27]. Results are obtained by employing bounds analysis techniques from which practical performance information and insight into expected token ring behavior can be obtained.

This paper will introduce the workings and a model for a non-priority token ring. Using this model we prove the operational bounds of the token ring Media Access Control (MAC) layer. Actual measured performance data will be presented as a verification of the results.

2 Token Ring Model, Specifications and Notations

A token and frames circulate on a token ring. Frames are composed of a number of fields which help control station access to the ring and carry data between stations on the ring. The token only controls access to the ring. To get a more detailed understanding of the physical layout and the workings of a token ring see [4].

The IEEE 802.5 standards specify the token holding time to be a maximum of 10 milliseconds. Some implementations are less (e.g. IBM uses 9 milliseconds). The standards imply that frame transmission time is limited to 10 consecutive milliseconds. Hence the token holding timer controls the amount of time the station can use the ring before passing the token to the next station.

Clearly frame size is limited by the following relationship.

$$\text{Size(bytes)} \leq ((10 \text{ msec } \times \text{RingSPD})/8 \; bits/byte)$$

In every token ring there is always one station which acts as the active ring monitor and manages the ring [4,5]. At the active monitor, buffers are inserted into the ring and delays equal to the buffer lengths are introduced. These delays serve two functions. First, they insure a minimum ring latency of at least 24 bits (3 bytes, which is the token size). Second, they compensate for phase jitter, which is accomplished using an elastic buffer. IEEE standards specify at least a six bit elastic buffer. Implementations may vary. Whenever a token/frame passes through a **ring station** there is a delay of approximately 4 bit times. Actual delays can vary depending on individual station hardware characteristics. For the j^{th} station we denote this bit time delay by δ_j. We will denote the speed at which bits are propagated on the ring by $f(L)$. Let P_j denote the packet size generated by of the j^{th} ring station at a given instance in time. Let n_i denote the number of token ring stations, r_i denote ring radius and SPD_i ring speed in millions of bits/second of the i^{th} ring. When a single ring is considered the subscripts are not used.

3 Motivation

Using specialized hardware developed at IBM, user defined ring characteristics can be monitored at high speed with negligible no impact to ring behavior. Table 1 shows data captured for a minimum size token

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ring with no activity except normal housekeeping operations. This data shows 30 seconds of second by second 16 Mb idle ring activity. The only event that occurs besides token activity is a nearest neighbor notification every seven seconds. Table 1 was obtained by constructing a "minimum size" token ring using a single IBM PS/2 model 70 with 10 feet of cable attached to an isolated IBM 8228 multistation adaptor unit (MAU). The number of tokens counted per second on the idle ring was much less than the 666,666 expected. If minimum ring latency was just the token size then 16,000,000/24 tokens would circulate the ring every second. Therefore, substantial buffering delays are effecting token circulation. These delays are being attributed to monitor operation.

Note, the authors have found that some token count differences among the data tables are due to ring speed variation of .01%, uncertainty in the "C++" DELAY function, and the PS/2, $\frac{1}{18}^{\text{th}}$ second, hardware timer which is used to time the intervals of data collection. These variations offer an error less than 1%.

It is a common but erroneous belief that ring latency can be as small as 24 bits. After every token, a gap is inserted (approximately 40 bits.) This "token gap" is different than the interframe gap of 40 bits transmitted after each frame transmission. Also, depending on the number of devices on the ring some elastic buffer bits will circulate with the token and the token gap will become larger. We have found the minimum ring latency is approximately (64 ± 2) bits under ideal conditions.

Elastic buffer activity (which changes the logical ring size) can be identified in the token count data in Table 1. The token count clusters at three values differing by approximately 7000 tokens in different one second time intervals. This data leads us to the conclusion that phase jitter compensation is taking place and ring latency is oscillating around a ring stability point. A simple calculation shows that an inter-token gap exists which averages 38.8 bits. Tables 2 through 5 show the impact to token circulation by inserting additional stations to our controlled 16 Mb test ring. These additional tables show 10 second data collection intervals. Longer data collection intervals of 20 and 30 seconds yielded consistent data that is not presented here.

Inspection of these tables allows the development of actual PS/2 token ring adaptor delay values attributed to non-monitor ring stations. These values (often referred to as latency) can be calculated from the token count differences when devices are added to the ring. Our data suggests that individual ring station delays on 16 Mb rings are much greater than the 2.5 bit delays claimed by some adaptor manufacturers.

Our test data supports the deterministic model used for our analysis and conclusions.

4 Model equations

In this section we will derive the basic equations for single token ring operation. Let us assume the j^{th} station in the ring is about to transmit a packet of byte size P_j. First a station must encode the frame onto the ring, this time is called the frame encoding time (t_0). Clearly, $t_0 = \frac{8P_j}{SPD}$, this is the time station j is busy transmitting a frame. Also, note that after t_0 seconds the last bit of the frame is on the ring.

Now when a bit from a frame gets on the ring it suffers the following delays before it gets back to the transmitting station. Propagation delay in seconds (PT) is given by $\frac{2\pi r}{f(L)}$, which is the delay in seconds for a bit to go around the ring. Initially we assume all stations have equal delay, hence we let $\delta_j = \delta$ for all j. We will use 4 bits as our typical δ value. The token ring test data shown in Tables 2 through 5 lead to δ values ranging from 3.5 bits to 4.5 bits.

Station delay can be expressed as $\frac{\delta(n-1)}{SPD}$ which is the time for a bit to go through each station (except the monitor), monitor delay in seconds is given by, $\frac{MD}{SPD}$. Let t_2 = Propagation Delay + Station Delays + Monitor Delay. Hence, $t_2 = PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD}$, which denotes the time for the first bit of the token or a frame to make it's way entirely around the ring. From the test data in Table 1 MD is calculated as 38.5 (RING SPD/#Token per sec - Token Size) bit times. Each station on a ring must relinquish the token after a transmission period of 10 milliseconds. By the standards it is possible to send multiple frames in this 10 millisecond interval. We will, however, in our model adhere to what is done in most commercial implementations where frame size is restricted and the token is released after every frame transmission. Without loss of generality we focus on investigating two typical implementations. *In one implementation (typically 4Mbs) a transmitting station releases a token when both of the following two conditions are true. In the other, only the first condition needs to be true which we refer to as early token release.*

- *Transmission of a single frame is completed.*
- *Leading edge of transmitted frame has returned.*

Even though this paper does not consider priorities, it is important to note that early token release may interfere with prioritization whenever frame sizes are smaller than the ring bit length (latency). **Token Rotation:** For a given station, token rotation is the time between the initial transmission of a frame and the next time a free token is available (and another frame can be transmitted). In a ring with only one very busy station this can be seen as the time between leading edges of successive frame transmissions (separated by a token transmission). Thus, token rotation is a variable depending on station activity and frame sizes.

5 Ring Behavior with No Early Token Release and No Priority

Assume a station is transmitting a frame. After the last bit is encoded on the ring, the first bit of the frame will have made its way thru part of the ring (depending on the frame and ring size) and may take some additional time to reach the sender. Let t_1 denote this additional time. Notice, the first bit traveling around the ring and the encoding activity of the other bits behind it occurs in parallel. If the frame is long then t_0 will reduce (or eliminate) the time t_1. Therefore $t_1 = MAX(t_2 - t_0, 0)$ whenever $t_0 > 0$.

1. Thus to analyze a station without early token release these cases need to be considered.
   (a) $t_0 \geq t_2 \Longrightarrow t_1 = 0$ (for $t_0 > 0$)
   (b) $t_0 < t_2 \Longrightarrow t_1 = t_2 - t_0$ (for $t_0 > 0$)
   (c) $t_0 = 0 \Longrightarrow t_1 = 0$

Best Utilization: We now present the equations for shortest token rotation and best utilization that can be achieved by any ***single station.*** Station transmission is controlled by the availability of the token and data. In a ideal situation an individual ring station access to the token is not limited by competition from other stations. Thus the frequency of token availability strictly depends of the physical characteristics of the ring. Hence, the shortest possible token rotation can be calculated by: $\sum_{i=0}^{2} t_i$. From Table 1, this value is approximately 4 microseconds during idle ring periods.

By definition, any station utilization is defined as busy time over total time. Total time consists of both busy and idle periods. In practice total time is highly subjective and heavily depends on the intended use of the utilization information. *For our purposes we will consider the token rotation interval as our basic time unit.* The best utilization (highest) for a station implies the idle period must be minimal. The station can accomplish this by insuring that there is no wait for data only the token. Hence, the best possible utilization (BUS) for any single j^{th} station for a fixed n is given by:

$$\mathbf{BUS_j} = \frac{t_0}{\sum_{i=0}^{2} t_i} = \frac{\frac{8P_j}{SPD}}{\frac{8P_j}{SPD} + MAX(t_2 - t_0, 0) + PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD}} \quad (1)$$

Now we define the utilization of the ring itself. The utilization of the ring **UR** is the sum of the utilizations of all the stations on the ring. Clearly the lowest utilization of the ring is zero, that is when none of the stations are active. From equation (1) and the definition of **UR** we will later show the maximum utilization of a token ring cannot be achieved with only one active station.

Worst Utilization: Here we derive equations for the longest token rotation time and worst utilization for a single station on a ring. Assume round robin scheduling with no priority. The longest token rotation time occurs when each of the n stations on the ring have data to send. The longest token rotation time becomes:

$$\sum_{i=1}^{n}\left[\frac{8P_i}{SPD} + Max\left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} - \frac{8P_i}{SPD}, 0\right]\right] + PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD}$$

Next we develop some notations to represent token rotation times as a function of the number of stations and their activity. Let a ring have n stations and $\vec{b} \in \{0,1\}^n$. IF i^{th} bit of $\vec{b}$ is one then it implies that the i^{th} station on the ring has data to send and zero if the station is idle. Let $\vec{b}(i)$ be the value of the i^{th} bit of $\vec{b}$. Now we will use $R^n(\vec{b})$ to denote the token rotation for any single station, on a ring with n stations, and some number of stations which have data to transmit which are given by non-zero positions of $\vec{b}$. Hence worst token rotation time for a single ring is expressed as:

$$R^n(1^n) = \sum_{i=1}^{n}\left[\frac{8P_i}{SPD} + Max\left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} - \frac{8P_i}{SPD}, 0\right]\right] + PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} \quad (2)$$

Also the worst utilization (WUS) for the j^{th} device is defined by:

$$\mathbf{WUS_j} = \frac{\frac{8P_j}{SPD}}{R^n(1^n)} \quad (3)$$

Ring utilization can be given by: $\sum_{j=1}^{n} WUS_j$. Incidentally, this represents the best possible ring utilization (**BUR**) which will be shown in the next section.

6 Ring Behavior With Early Token Release and No Priorities

The previous section provided token ring operation that is described by IEEE 802.5 standard. A careful analysis of the best station utilization (equation 1) will show that it's limited by the combination of packet size and ring speed. As ring speed increases the encoding delay (t_0) decreases significantly and severely limits the utilization by any individual station (since t_2 is a constant and t_1 becomes significant). Because of this factor some implementations (e.g. FDDI and

IBM 16 Mbs) allow the token to be released immediately following the transmission of a frame unlike the 802.5 specification where the station has to wait for the transmitted frame to return before it releases the token. This eliminates any t_1 delay and interferes with prioritization. We refer to this as early token release.

To develop equations for shortest token rotation time, with early token release, we view ring activity from the first bit of a frame leaving a station. This bit leaves station A, travels around the ring and arrives back at station A in time $PT + \frac{(n-1)\delta}{SPD} + \frac{MD}{SPD}$

Also the size of the frame must be considered because we have to read past the frame to get to the token. We need the term $\frac{8P}{SPD}$ to describe frame encoding time. Hence the shortest token rotation time can be given as:

$$R^n(10^{n-1}) = \frac{8P}{SPD} + PT + \frac{(n-1)\delta}{SPD} + \frac{MD}{SPD} \quad (4)$$

Therefore the best possible utilization for the j^{th} station ($\mathbf{BUS_j}$) is given by:

$$\mathbf{BUS_j} = \frac{\frac{8P_j}{SPD}}{R^n(10^{n-1})} \quad (5)$$

This is intuitive because (from a station's point of view) there is always a non-productive transmission period from the first bit of the token until the token makes its way around the ring and another frame can be released. With a single transmitting station no one else will use the token and this non-productive period can be minimized.

The longest possible token rotation time is derived assuming round robin scheduling with no priorities. For a worst case, each of the n stations on the ring must have data to send. Clearly, since each station has data to send, the station which just released the token must wait till all the other $n-1$ stations have transmitted frames. This maximizes the stations non-productive period. Therefore the longest token rotation time for a ring with n stations is given by:

$$R^n(1^n) = \frac{8\sum_{i=1}^{n} P_i}{SPD} + PT + \frac{(n-1)\delta}{SPD} + \frac{MD}{SPD} \quad (6)$$

Therefore the worst utilization for station j ($\mathbf{WUS_j}$) is given by:

$$\mathbf{WUS_j} = \frac{\frac{8P_j}{SPD}}{R^n(1^n)} \quad (7)$$

Combining our previous equations for longest case token rotation time produces the following equations if early token release is treated as YES/NO question. Hence

$$\Delta = \begin{cases} 0 & \text{if Early token release} \\ 1 & \text{if No early token release} \end{cases}$$

$$R^n(1^n) = \sum_{i=1}^{n} \left[\frac{8P_i}{SPD} + \Delta \times Max \left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} - \frac{8P_i}{SPD}, 0 \right] \right] + PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD}$$

Using the Δ function and $\vec{b}$ which specifys the number of busy devices a general equation for token rotation time with or without early token release can be given by:

$$R^n(\vec{b}) = \sum_{i=1}^{n} \left[\frac{8P_i}{SPD} + \Delta \times Max \left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} - \frac{8P_i}{SPD}, 0 \right] \right] \vec{b}(i) + PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} \quad (8)$$

Using equation (8) a general expression for the utilization of station (US_j) j can be given as

$$\mathbf{US_j} = \frac{\frac{8P_j}{SPD}}{R^n(\vec{b})} \quad (9)$$

We show that station utilization is bounded by equation (5) and (7) in the next section. A general expression for ring utilization can be given as

$$\mathbf{UR} = \sum_{i=1}^{n} US_i \quad (10).$$

In addition, ring utilization (UR) is shown to have similar bounds as station utilization. Equations (9) and (10) are of limited practical value because they convey utilization information within an extremely small time frame (i.e. one rotation). Token rotation is logically the limiting case that results can be built upon. For longer time frames activity needs to be summed over all token rotations within the time frame. This concept is expressed in equations (11) and (12) when r rotations occur. The utilization of station j with r rotations is given by:

$$\mathbf{USr_j} = \frac{\mathbf{US_j^1} + \mathbf{US_j^2} + \cdots + \mathbf{US_j^r}}{r} \quad (11)$$

Ring utilization with r rotations is given by:

$$\sum_{i=1}^{n} USr_i \quad (12)$$

Typically utilization is calculated using media speed as the denominator in many equations. This can lead to errors. Equations (11) and (12) allow a more accurate calculation by considering the fact that during some portion of each token rotation the media is unavailable and should not be considered usable bandwidth during this time frame.

7 Analysis and Results

In this section all the results that we derive will assume single ring with speed SPD, propagation delay PT and n stations. (Note: priority will not be considered.)

Theorem 1. A ring with early token release has no advantage in performance over a ring without early token release if for every frame P_i,

$$P_i \geq \frac{\left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD}\right]SPD}{8} \tag{13}$$

Proof: Since performance depends on token rotation, to prove the above result it is sufficient to show that the token rotation time for both cases are the same if packets sizes are sufficiently large (i.e. satisfy equation (13)). Suppose

$$P_i \geq \frac{\left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD}\right]SPD}{8} \tag{14}$$

then

$$\left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} - \frac{8P_i}{SPD}\right] \leq 0$$

therefore

$$Max\left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} - \frac{8P_i}{SPD}, 0\right] = 0$$

Now by equation (8) which is the token rotation for both early and non early token release the result follows. □

Using the data from the Table 2 we calculate token rotation for our test 16 Mbs ring to be 62.5 bits. Thus, from Theorem 1 we need frame sizes less than 8 bytes before early token release provides a performance gain. All token ring frame sizes are at least 21 bytes. Therefore, ring latency in terms of propagation delay or station delay must sum to over 168 bits before we can consider any positive impact due to early token release. We can see from the cumulative station delays derived from the test data in the Tables that early token release may improve performance as the number of stations exceeds 27 (the n value in equation 13). Obviously this value rises as the frame size increases and is influenced by cable propagation delay (which is usually a minor LAN consideration).

Corollary 2. If all the frames transmitted by the stations do not satisfy equation (13) then ring and station utilization with early token release is better than ring and station utilization without early token release.

Proof: Follows from equations (8), (9), (10) and Theorem 1. □

Corollary 3. For high ring speeds, early token release is necessary for maximum utilization.

Proof: Note that the frame sizes in any token ring is bounded (due to the token holding timer). Hence when speed increases, the packet sizes will not satisfy equation (13). Therefore by Theorem 1, early token release has an advantage over no early token release and this advantage is significant as ring speeds increase. □

Theorem 4. Consider two identical token rings, ring one and ring two. Increase the speed of ring two. For both early and non early token release $UR(1) > UR(2)$, where $UR(1)$ and $UR(2)$ are the utilization of ring one and ring two.

Proof: Let the speed of ring one and two be SPD_1 and SPD_2 respectively. Then using equation (10) and some algebra we can show that $[UR(1) - UR(2)]$ is positive. □

Theorem 1, its corollarys, and Theorem 4 present opposing view points of the effectiveness of early token release with respect to frame sizes and ring speeds. One view purports that when frame sizes are large enough early token release is not required and the other says its required as ring speeds increase. These results gives us some insight into the necessity for early token relase token ring implementations (e.g. FDDI). If frame sizes (or transmission activity) are restricted for any reason and ring speeds grow then inefficiency in ring operation without early token release is due to the t_1 delay becoming a severe utilization constraint. Typically, for 4 or 16 Mbs rings, t_1 becomes non-existent as frame sizes exceed 100 bytes for any of the largest existing rings found installed today. For current FDDI implementations and its proposed follow on (at 640 Mbps), the t_1 delay is clearly a problem requiring early token release. In addition, the number of stations on a ring has the greatest impact on overall performance since numbers like 4.0 bit delays per station represent a large delay when compared to (cable) propagation delay.

Theorem 5. If any station has data to send, it will eventually be sent, i.e. every device on the ring has at least some thruput.

Proof: For any station the worst case token rotation time is $R^n(1^n)$ which is finite (note priority is not considered). Hence the token must eventually arrive at that station. Hence the station can transmit data. □

Theorem 6. Assume each station i transmits packets of size P_i during any token rotation. Then the best ring utilization occurs when every station on the ring has data to transmit. When this occurs individual station utilization is at the minimum.

Proof: To prove this result, we show that the utilization of the ring goes up when there is a increase in the number of stations which are transmitting. Assume m_1 devices on the ring ($m_1 < n$) are transmitting. Then by equation (9) the utilization of station i is $\frac{\frac{8P_i}{SPD}}{R^n(\vec{b})}$ where $\vec{b}$ specifys the activity of the m_1 stations. Let the frame encoding time for station i be given as $c_i = \frac{8P_i}{SPD}$ and $q_i = \Delta \times Max\left[PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD} - \frac{8P_i}{SPD}, 0\right]$ and $t = PT + \frac{\delta(n-1)}{SPD} + \frac{MD}{SPD}$. Note that for a given ring t is a constant. Therefore the utilization of station i is

$$\frac{\frac{8P_i}{SPD}}{R^n(\vec{b})} = \frac{c_i}{\sum_{i=1}^{n}(c_i + q_i)\vec{b}(i) + t}$$

The proof is conclded by considering early token release and non early token release cases.□

Theoretically, the best throughput for a station occurs when it is the only one transmitting. But current station technology is the bottleneck and limits this theorem's applicability today. Most commercial token ring adapter technology is limited to 3000 frames per second. This is changing as more efficient "next generation" adaptors are manufactured and sold.

Theorem 7. Assume each station i transmits packets of size P_i during any token rotation. Then the best possible utilization for a single station is when it is the only station transmitting. This results in the worst utilization for the ring.

Proof: From the previous theorem the utilization of station i is

$$\frac{c_i}{\sum_{i=1}^{n} c_i\vec{b}(i) + t} \qquad (a)$$

and the utilization of the ring is

$$\frac{\sum_{i=1}^{n} c_i\vec{b}(i)}{\sum_{i=1}^{n} c_i\vec{b}(i) + t} \qquad (b)$$

For any station, its utilization is maximum when the denominator of equation (a) is minimum. This occurs if and only if the i component of $\vec{b}$ is non-zero. When this condition is true then equation (b) reaches its minimum by Theorem 6. □

Theorem 6 and 7 form the basis for the evaluation of expected ring and station behavior in various ring environments. Expected utilization of both the ring and each individual station is clearly bounded. Furthermore, if we observe ring behavior over multiple token rotations it is clear that theorems 6 and 7 remain true even if individual stations have varying packet sizes.

Observe that the thruput in packets per second for individual stations and the ring itself is given by $\frac{1}{R^n(\vec{b})}$ and $\frac{\sum_{i=1}^{n}\vec{b}(i)}{R^n(\vec{b})}$ respectively. These equations ignore the impact of packet sizes.

8 Extended Analysis

From the previous section it is apparent that attachment of additional stations to a token ring will impact performance. Therefore, we no longer consider uniform δ values for all ring stations. Depending on the delay and buffer characteristics of the new station, performance can improve, degrade or stay the same. Also, the propagation delay of the additional length of "wire" needed to attach a new station to a ring should be a part of the δ value, since propagation delay impact is very pronounced at high speeds. Hence, the installation of a station can be categorized as efficient or inefficient with respect to a particular ring composition. Therefore station characteristics and distance can become critical performance constraints depending on the scale of the ring implementation.

Definition: Given a ring with speed SPD, early token release and n active stations, with each station transmitting a packet of size P_i and δ_i bit delays for each station, a new station being attached to this ring is said to be efficient if and only if

$$\delta^* < [MD + PT \times SPD + \sum_{i=1}^{n-1} \delta_i]\frac{P_{n+1}}{\sum_{i=1}^{n} P_i}$$

where δ^* is the delay in bits and P_{n+1} the packet size transmitted, by the new station.

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where δ^* is the delay in bits and P_{n+1} the packet size transmitted, by the new station.

From these definitions it is apparent that the frame sizes transmitted by the new station will influence the efficiency determination of adding a new station to an existing ring implementation. However the impact of the new stations frame size is greatly diminished as the number of stations on the ring becomes large.

The next theorem shows a surprising result. That is, whenever we attach a new station to a ring the maximum ring efficiency goes up if the station is efficient and it goes down if the station is inefficient and stays the same otherwise.

If the following theorem is applied to pizza, the pie will get larger as more "efficient" people are served.

Theorem 8. Given a ring with early token release, n active stations with the i^{th} station transmitting packets of size P_i, and propagation delay PT, attaching a new station on the ring which transmits a packet of size P_{n+1} will increase the UR of the ring if the new station is efficient and decrease the UR if the new station is inefficient. Utilization stays the same otherwise.

Proof: Assume an efficient attachment. By equation (10) utilization of the ring before attaching the new ring is:

$$\frac{\frac{\sum_{i=1}^{n} 8P_i}{SPD}}{\frac{\sum_{i=1}^{n} 8P_i}{SPD} + PT + \frac{\sum_{i=1}^{n-1}\delta_i}{SPD} + \frac{MD}{SPD}} \qquad (a)$$

By equation (10) utilization of the ring after attaching the new ring is:

$$\frac{\frac{\sum_{i=1}^{n+1} 8P_i}{SPD}}{\frac{\sum_{i=1}^{n+1} 8P_i}{SPD} + PT + \frac{\sum_{i=1}^{n-1}\delta_i}{SPD} + \frac{\delta^*}{SPD} + \frac{MD}{SPD}} \qquad (b)$$

Note that we assume all stations are active.

Lets suppose the ring utilization decreased after the attachment of an efficient station. This implies that $(a) > (b)$. Now by using some algebra we can arrive at the following inequality:

$$\delta^* > [MD + PT \times SPD + \sum_{i=1}^{n-1} \delta_i] \frac{P_{n+1}}{\sum_{i=1}^{n} P_i}$$

This contradicts the hypothesis the attached station is efficient. □

The previous theorem shows that the token and frame passing delays of stations attached to the ring impact performance. Theorem 8 can be of use predicting both ring and station performance when attaching a new station to an existing ring. When propagation delay is considered as part of δ the impact of δ becomes substantial. For example, at the speed of light, a bit occupies approximately two hundred and forty five foot of 4 Mb ring (approximately 61 foot of a 16 Mb ring). Since packet sizes are restricted, the distance of a new station from the existing ring will usually decide if it acts as an efficient or inefficient station. Clearly, if the station is placed too far from a high speed ring it becomes inefficient. Thus, stations that are geographically dispersed may be better connected using multiple rings and establishing bridges between them. This minimizes the MAC layer performance impact to existing ring stations by keeping token rotation time small. Thus, the propagation delay associated with any geographically dispersed stations are "localized" by the bridge connection and do not effect ring protocol operation.

Theorem 9. Assume a ring with all stations transmitting a packet of size P. Then a new station with a δ^* that is the average of the δ_i's of the existing ring station is an efficient station.

Proof: Let $\delta^* = \sum_{i=1}^{n} \delta_i / n$. Suppose the new station is an inefficient station then

$$\delta^* > [MD + PT \times SPD + \sum_{i=1}^{n} \delta_i] \frac{P_{n+1}}{\sum_{i=1}^{n} P_i}$$

Now since the packet sizes are the same this implies that

$$\delta^* > [MD + PT \times SPD + \sum_{i=1}^{n} \delta_i] \frac{P}{nP} \qquad (15)$$

This implies $[MD + PT \times SPD]/n < 0$ which is a contradiction. □

Equation (15) in Theorem 9 is dominated by monitor delay in usual implementations. Therefore in practice efficient stations can be easily found for small lightly loaded rings.

Theorem 10. For all stations a ring speed exists at which they are efficient.

Proof: Let the new station have a delay δ^*. For a particular ring there exits a speed for which

$$\delta^* < [MD + PT \times SPD + \sum_{i=1}^{n} \delta_i] \frac{P}{nP} \qquad (16)$$

hence result. □

Equation (14) suggests that in order to compensate for attaching an inefficient station, the SPD increase must be proportional to the number of stations on the ring. While theoretically SPD can be increased to overcome the inefficiency introduced by a new station, the amount of increase required usually renders this approach impractical.

Theorem 11. Given a ring with n stations attaching a new station on the ring will reduce BUS_j for all j.

Proof: For any j $R^n(10^{n-1}) < R^{n+1}(10^n)$. The result follows from equation (5). □

This result extends for any fixed load. This is true once token rotation time is increased, then utilizations of individual stations decrease.

9 Summary and conclusions

Our measurements and analysis show that a token ring LAN is capable of good "shared media" performance for many high bandwidth applications, even at high offered load. Unlike Ethernet very high loads are sustainable without bandwidth loss due to retransmissions. The performance of a token ring can be best understood by using the token rotation concept. We found that token rotation times are directly impacted by packet size, the number of devices on the ring, their activity and ring latency. In addition a deterministic analysis technique is capable of providing good insight into MAC layer ring dynamics and directly generates useful results. Our results allow the determination of bounded delay to access the media, when to split a ring, when to use early token release, the impact of cable length and accurate expected utilization.

References

1. A Survey of Light-Weight Transport Protocols for High-Speed Networks; W. Doeringer, D. Dykeman, M. Kaiserwerth, B. Meisner, H. Rudin and R. Williamson; IEEE Transactions on COMMUNICATIONS, November 1990, vol 38, 11, p 2025.

2. FDDI - A LAN Among MANs; F.E. Ross, J.R. Hamstra, R.L. Fink; Computer Communication Review, vol 20,3 July 1990.

3. High-Speed Local Area Networks and Their Performance: A Survey; B.W. Abeysundara and A.E. Kamal; ACM Computing Surveys, vol 23, 2 June 1991.

4. IBM Token-Ring Network Architecture Reference SC30-3374 September 1989.

5. Local Area Network, Technical Reference, IBM Corporation, SC30-3383.

6. Local Area Networks: The New Utility; Thomas Toher; Personal Systems, IBM personal Systems Technical Solutions, Issue 3, 1991.

7. Measured Capacity of an Ethernet: Myths and Reality; D.R. Boggs, J.C. Mogul and C.A. Kent; Communications Architectures & Protocols, SIGCOMM '88 SYMPOSIUM, Stanford, California, August 16-19, 1988.

8. Modeling and Analysis of Local Area Networks; P.J. Foster and G. R. Desrochers; CRC press 1990, ISBN 0-8493-7405-7.

9. Multimedia Applications on IBM TOKEN-RING LANs; K.Amer, K. Christensen and T. Toher; Personal Systems, IBM personal Systems Technical Solutions, Issue ? 1993.

10. NetWare Communications and Routing Protocols; Paul Turner; Personal Systems, IBM personal Systems Technical Solutions, Issue 3, 1991.

11. New Horizons for IBM's Shielded Twisted-pair Cabling; H. Foglia and T.Toher; Personal Systems, IBM personal Systems Technical Solutions, Issue 3, 1991.

12. Overview of Metropolitan Area Networks; Robert W. Klessig; IEEE Communications, vol 24, 1 January 1986.

13. Performance Analysis of Carrier Sense Multiple Access with Collision Detection; F. A. Tobagi and V. B. Hunt; Computing Networks, vol 4, 1980, p 245.

14. Performance of the IEEE 802.2 Type-2 Logical Link Protocol with Selective Retransmissions; E.W. Biersack; IEEE Transactions on COMMUNICATIONS, February 1993, vol 41, 2, p 291.

15. Proactive LAN Management; Mary Jander; Data Communications, March 1993.

16. Remote Local Area Network Management Tools; D.J. Mieczkowski and M. W. Boswell; Personal Systems, IBM personal Systems Technical Solutions, Issue 3, 1991.

17. Tuning and Self-Tuning Features of OS/2 LAN Server; Tom Gorday; Personal Systems, IBM personal Systems Technical Solutions, Issue 3, 1991.

18. Tuning Your Network's Performance; Dan Nassar; LAN Technology, April 1993.

Token Counts Per Time Period

Table1	Table2	Table3	Table4	Table5
261741	2552469	2405530	2278971	2153105
254709	2559502	2405544	2285261	2147201
254706	2559503	2405531	2285245	2147220
254708	2559496	2405542	2285261	2147205
261744	2559501	2405530	2285245	2147201
254716	2559499	2405545	2285263	2147223
254703	2550503	2412149	2285265	2147184
254708	2559498	2405532	2285244	2147222
254709	2559500	2405540	2285258	2147202
247678	2559505	2405532	2285243	2147205
254715	2559494	2405540	2285263	2147220
254711	2559407	2405531	2285245	2147201
254708	2566530	2405542	2285259	2147203
261737	2559505	2405543	2285261	2147200
254713	2559497	2405536	2285244	2147222
254708	2559504	2405541	2278984	2147189
254708	2559500	2405531	2285245	2153121
261742	2559497	2405540	2285259	2147220
254711	2559501	2405534	2285247	2147185
254709	2559496	2405545	2285261	2147221

Table 1: One device on the ring; (minimum size 10' of cable). Station "A" active per second.
Table 2: One device on the ring; (minimum size 10' of cable). Station "A" active per 10 seconds.
Table 3: Two devices on the ring. Stations "A" and "B" active per 10 seconds.
Table 4: Two devices on the ring. Stations "A", "B" and "C" active per 10 seconds.
Table 5: Two devices on the ring. Stations "A", "B", "C" and "D" active per 10 seconds.