A Buffer insertion priority mechanism based on the IEEE 802.4 priority scheme

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of MASTER OF SCIENCE in Computer Engineering

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Abstract

The focus of this thesis is to investigate a media access priority mechanism for a buffer insertion network so that it is better suited for use in real-time applications. This is done by examining a popular priority mechanism present in the IEEE 802.4 token bus standard, and Fiber Distributed Data Interface (FDDI) standard. Mathematical models for throughput and delay are presented for the IEEE 802.4 priority mechanism. These models are then used as a basis for developing the priority mechanism for the buffer insertion ring. Models for throughput and delay are also presented for the buffer insertion priority scheme so that the two media access techniques may be compared.
1. Introduction

There are many popular media access techniques for distributed systems. Among the most popular are

- first come first served,
- carrier sense multiple access (CSMA),
- token passing,
- buffer insertion,
- and slotted rings.

Of these, only a few have been defined or implemented with a priority mechanism in mind. This is true for many reasons. Perhaps the media access protocol does not lend itself easily to priority transmissions, or perhaps the application running on the network is not very time critical and does not need prioritization of data transfers.

Without a priority mechanism, the media access protocol has no way of getting high priority transmissions to their destinations in a timely manner. The frames must wait for access to the media following the same constraints as every other frame awaiting transmission. This means that important data may have to wait for access to the media because less important data is hogging the bandwidth. One way to avoid this problem is by assigning all outgoing frames a priority. Based on the definition of the priority mechanism, the priority assigned to a frame will help dictate when it gains access to the medium. Lower priority frames yield to the transmission of higher priority frames.

1.1. Goals

The goals of this thesis are to

- study a well designed, documented and accepted priority mechanism,
- and use this knowledge in developing a priority mechanism for a buffer insertion protocol.
The priority mechanism that will be studied is defined in the IEEE 802.4 token bus standard. This priority mechanism is also very similar to that used in the Fiber Distributed Data Interface (FDDI) standard. Section 2 gives a functional description of the priority scheme. It then goes on to develop models for throughput and media access delay. These models will aid in both understanding the IEEE 802.4 priority mechanisms, and in developing a similar priority mechanism for the buffer insertion protocol.

The buffer insertion protocol is chosen as a candidate for the development of a priority mechanism because of its uniqueness as a media access protocol, and its inability to meet real-time constraints under heavy loading conditions. Without any type of priority mechanism, the buffer insertion protocol displays a steady increase in media access delay as the throughput of the system increases. This is not satisfactory for real-time applications that must guarantee a maximum media access delay and delivery time for a certain message class. In addition, the buffer insertion protocol allows for starvation to occur. This will occur when a node is prohibited from accessing the network because of the heavy usage from other nodes. Starvation is also unsatisfactory in real-time distributed applications.

A well-designed priority mechanism should allow for graceful degradation of the communications system. That is to say, when the offered load to the network exceeds its bandwidth capabilities, more important messages (messages of higher priority) will be the first to reach their destinations. Less important data will be the first to suffer due to the high load. If the load was to continue increasing, the performance of the network would degrade in a graceful way.
Ignoring the negative remarks about the buffer insertion protocol stated above, it does have many intriguing features that make it an attractive choice for real-time systems. This is especially true with respect to token passing protocols. The overhead involved in token passing, token regeneration, and duplicate token detection, is no longer needed in a buffer insertion ring. Also, the buffer insertion algorithm allows for multiple transmissions to be occurring simultaneously. This is called *spatial reuse*, and allows for throughput exceeding the capacity of the media. Both characteristics amount to better use of the media for all types of transmissions. In other words, looking at total network throughput is attractive to real-time applications, but the media access delays associated with these high throughputs are the problem.

Section 3 gives a functional description of the priority mechanism proposed for the buffer insertion protocol. This is followed by the development of mathematical models for throughput and access delay. The final section discusses the results of the buffer insertion priority mechanism when compared to the models for the IEEE 802.4 token bus priority scheme.
2. Analysis of the IEEE 802.4 Priority Mechanism

2.1. Background

Priority mechanisms in loosely-coupled distributed systems play a significant role in how a network will perform under high loading conditions. Any media access protocol (MAC), even one that doesn't incorporate a priority mechanism, can perform satisfactorily within the operational constraints of the media. What is considered here is how a network will perform when the offered transmission load begins to exceed the available bandwidth for a given time. Performance over a network whose media access protocol does not incorporate priority transmissions will suffer. This is because the protocol has no way of discerning important data from unimportant data. Data is transmitted in a first-come-first-served fashion. If the network is being used in a real-time application such as process control, the consequences could be disastrous. A media access priority mechanism understands which of the data queued for transmission is the most time critical, and which is not. More important data will be transmitted sooner than less important data.

The IEEE 802.4 standard incorporates a media access control (MAC) protocol that uses a priority transmission mechanism. The MAC layer is a sub-layer within the bounds of the OSI architecture's datalink layer. A bus topology is usually associated with the IEEE 802.4 priority mechanism. This, however, does not have to be the case. FDDI also uses a priority mechanism that is very similar to the IEEE 802.4 protocol, and FDDI is a token passing ring network. It is safe to say that the priority mechanism being detailed in this section could be used in any token passing network. It is not dependent on the underlying physical topology. Although the token bus topology is discussed
throughout the document, it is important to remember that the protocol is just as easily implemented in a token-passing ring network.

The IEEE 802.4 token bus expects stations to be configured along a linear bus, but treats the bus as a logical ring. It is important to note that the physical ordering of the nodes on the bus does not affect the order of token passing. Since every station connected to the bus hears every transmission, the token is usually addressed to a specific node that is the next lower device address. The station with the lowest device address obviously has to address the token to the station with the highest device address. The specification of the physical layer is not important for our purposes, but the bus is usually made up of 75-ohm broadband coaxial cable. Transmission rates of 1, 5, and 10 Mbits/sec are possible.

2.2. Introduction

The IEEE 802.4 token bus network has become a standard in the industrial automation industry. The reason for its acceptance lies in three main areas. These areas are

- stability,
- reliability,
- and a priority mechanism.

The IEEE 802.4 priority mechanism allows an industrial network to meet rigid real-time requirements. Also, it allows additional bandwidth to be used for traffic associated with applications that are not time critical, or whose real-time requirements are not as stringent. This is done by allowing stations to access the medium synchronously and asynchronously. For high priority transmissions, each station has a guaranteed amount of time for each token rotation in which it may transmit. This is guaranteed bandwidth whatever
the total communication load. For lower priority transmissions, each station may or may not receive an opportunity to transmit for each rotation of the token. Gaining access to the medium for lower priority transmissions is based upon the overall communication load.

The following sections discuss the IEEE 802.4 priority mechanism. A functional description of the priority mechanism is given, followed by mathematical models that analyze the effects that the priority mechanism has on throughput and media access delay.

2.3. Functional Description

The IEEE 802.4 priority mechanism is described from a functional standpoint in this section. The description breaks down the priority mechanism into three major groups;

- priority levels,
- access classes,
- and timers.

Each of these areas and their interrelationships is discussed.

A complete description of the priority mechanism is presented below in structured English. The reader is encouraged to refer to this top-level description while reading later the sections explaining the usage of the high priority token hold time and target rotation timers. The IEEE 802.4 priority mechanism is now presented.

1. wait for token
2. start high priority token hold timer
3. transmit level 6 data until high priority token hold timer expires or there is no more level 6 data to be transmitted.

4. stop high priority token hold timer

5. pass the token internally to access class 4

6. calculate the level 4 token holding time by storing the remaining time left on the level 4 target rotation timer

7. restart the level 4 target rotation timer

8. if the level 4 token holding time is greater than 0 then transmit level 4 data until the level 4 token holding time is reached or there is no more level 4 data to be transmitted

9. pass the token internally to access class 2

10. calculate the level 2 token holding time by storing the remaining time left on the level 2 target rotation timer

11. restart the level 2 target rotation timer

12. if the level 2 token holding time is greater than 0 then transmit level 2 data until the level 2 token holding time is reached or there is no more level 2 data to be transmitted

13. pass the token internally to access class 0

14. calculate the level 0 token holding time by storing the remaining time left on the level 0 target rotation timer

15. restart the level 0 target rotation timer

16. if the level 0 token holding time is greater than 0 then transmit level 0 data until the level 0 token holding time is reached or there is no more level 0 data to be transmitted

17. pass the token to the next station in the ring

18. repeat

2.3.1. Priority Levels

The IEEE 802.4 priority mechanism offers four priority levels at which data may be transmitted. These priority levels are named 0, 2, 4, and 6, with 6 being the highest
priority. A station connected to an 802.4 token bus may be configured to use any combination of these priority levels, or no priority mechanism at all. A station not configured to use the priority mechanism automatically defaults to transmitting its frames at priority level 6. Whatever a station's configuration, it can coexist with other stations on the bus using different priority level configurations. For the purposes of this discussion, it is assumed that the stations are configured to use all available priority levels.

2.3.2. Access Classes

Access classes are the entities responsible for servicing each priority level within a single station. One access class exists for every priority level for which the station is configured. For example, a station configured to use all four priority levels will have four access classes. They are named access class 0, 2, 4, and 6, after the priority levels that they service.

Access classes can be thought of as virtual substations. Each access class present in a station has its own queue to store outgoing frames, receives the token, transmits frames, and transmits the token. However, for a station configured to use all four priority levels, only access class 6 receives the token from physical medium, and only access class 0 transmits the token onto the physical medium. At all other times the token is being passed internally within the station. Figure 1 shows this for a bus topology.
In Figure 1, the path of the token is shown by the dotted lines with arrows. The large boxes represent physical stations on the bus. Each box is divided into four smaller boxes to represent the virtual substations or access classes within each station. Each access class is labeled with its priority directly above it. Notice how access class 6, the highest priority access class, receives the token first within each station. It then passes the token internally to access class 4. Access class 4 internally passes the token to access class 2, and so on. When the token is finally transmitted from access class 0, it is physically sent on the media to the next station in the ring.

When an access class receives the token, and has data to transmit, it never passes the frame internally to the next lower priority access class. Each access class within a station transmits data directly onto the physical medium. Similarly, each access class maintains its own queues for holding data pending arrival of the token. Queues are not shared among access classes.
2.3.3.  Timers

Once the token is received, an access class uses a dedicated timer to track how long data transmission, at its priority level, can last. Depending on the priority level associated with the access class, the access class uses one of two types of timers;

- a high priority token hold timer,
- or a target rotation timer.

The amount of time that an access class is allowed to transmit is determined depending on the priority level associated with it. Lower priority access classes use target rotation timers to determine transmission duration, while access class 6 uses the high priority token hold timer.

2.3.3.1.  High Priority Token Hold Timer

Whenever a level 6 access class receives the token, the amount of data that will be transmitted before the token is passed is determined by one of two things;

1. the offered load at that priority level,
2. or the duration of the high priority token hold time.

In other words, the high priority token hold timer places an upper bound on the amount of data that a level 6 access class may transmit per token rotation. When the token arrives, the high priority token hold timer is started, and data transmission begins. When the timer expires, the current transmission is completed and the token is passed internally to the next lower priority access class, or to the next station if no other access classes exist. If the access class runs out of data to transmit before the high priority token hold
timer expires, the timer is stopped and the token passed onward. If the time needed to transmit the frame on the front of the queue is greater than the high priority token hold time, only one frame will be transmitted per token rotation.

The high priority token hold time is a configurable parameter in the IEEE 802.4 standard. It may be configured differently for every station in the network using access class 6, but usually all stations using access class 6 are configured for the same duration. This means that every node on the control network will have a reserved bandwidth in which it may transmit level 6 frames. Having a reserved bandwidth means that whatever the communications load, every node can transmit level 6 frames upon the arrival of the token. This will be guaranteed. The configuration of the high priority token hold timer, for real-time networks, is discussed in section 2.4.

2.3.3.2. Target Rotation Timers

The amount of time the lower priority access classes are allotted for data transmission are also governed by timers. The target rotation time is the maximum token rotation time that can occur in order for data transmission to take place from an access class. Within a station, these timers are used in all access classes except access class 6, which uses the high priority token hold timer to determine transmission duration. When a token arrives at a lower priority access class, the amount of time left before the target rotation timer expires is noted. This time is called the token holding time. After the token holding time is saved, the target rotation timer is reset and restarted. If the token holding time was noted as greater than 0, the access class is allowed to transmit data for the duration of the token holding time. If the token holding time expires in the middle of
a data transmission, then that transmission is completed. If the access class does not have any more data to transmit, but its token holding time has not yet expired, the token is passed early. If the access class's token holding time was 0, then its target rotation timer expired before the return of the token, and no data transmission is allowed from that access class for that token rotation.

The target rotation times for priority levels 0, 2, and 4, are configurable parameters in the IEEE 802.4 standard. They may be configured differently for every station on the token bus, but usually all stations using a particular access class are configured for the same duration. Also, the higher priority access classes are normally configured with larger target rotation times. This means that they have a higher probability of transmitting per token rotation.

It is important to note that the target rotation time for a particular access class determines the maximum amount of bandwidth available to all nodes transmitting that level frame per token rotation. The actual bandwidth available for any priority level is dependent on the number of other priority frames that are transmitted.

To understand why this is so, let's first assume that network traffic is made up of a single priority level other than level 6. This means that the target rotation time alone determines the total bandwidth available for this priority level frame per token rotation. If a single node transmits for its maximum token holding time, then no other nodes can transmit for that token rotation. Every other node on the network will receive the token after its target rotation timer has expired. Now, let's add network traffic comprising of data that is of higher priority, including level 6 frames. The available bandwidth of our priority level may drop to 0 if enough higher priority level frames are transmitted. If the
priority level in question is level 2, then priority level 6 traffic, priority level 4 traffic, or a combination of the two may use the available priority level 2 bandwidth. If priority level 4 transmissions are using the entire level 4 target rotation time, then no bandwidth will be left for level 2 transmission, whatever the level 6 traffic. This is assuming, of course, that the target rotation time for level 4 is larger than that for level 2. Similarly, level 6 traffic may use available level 2 bandwidth if many nodes have level 6 frames to transmit.

2.4. Meeting Real-Time Requirements

The priority mechanism inherent in the IEEE 802.4 standard may be configured so that it works efficiently for many different networking applications. The main concern of this section is to detail how the high priority token hold time and the target rotation times may be configured to meet real-time requirements across the control network. The particular area of real-time communication discussed in this section is process control. The network data associated with process control is broken down into categories. The configuration of the IEEE 802.4 priority timers is discussed for each category.

2.4.1. Alarm Messages

Alarm messages are usually associated with malfunctions in the process control equipment. Messages such as these are generated from a single board computer that comprises a single station on the control network. There are usually no external storage or display peripherals associated with it. In order for the alarm message to reach the operator, the message must be transmitted onto the control network. The alarm message is

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destined for a node or group of nodes that will respond immediately to the malfunction. Part of the control network will be placed in a fail-safe condition, and plant operators will be informed throughout the plant on display devices. If alarm messages are lost, or take a long time to reach their destinations, a dangerous situation may result.

Since alarm messages are so important in the process control environment, they should be transmitted as priority level 6 frames. This means that every node on the control network will have a reserved bandwidth in which it may transmit alarm messages. The duration of the transmission is determined by the high priority token hold time. Every node can transmit alarm messages upon the arrival of the token, whatever the load on the communication network.

2.4.2. Control Data and Network Maintenance

After alarm messages, data directly related to the process being controlled is the next most important group of messages on the control network. This data may be transmitted synchronously or asynchronously between nodes on the system to maintain control of the process. Of equal importance is network maintenance. Network maintenance messages consist of messages that allow nodes throughout the network to track the accessibility of various destinations. If important data must reach a particular destination, but the destination is down or for another reason is inaccessible, then the source of the transmission must act appropriately. Typically, this means sending an alarm message. Network maintenance messages also handle the addition and deletion of nodes to the logical ring dynamically. The network does not have to be rebooted every time a node is added.
to the logical ring, and does not crash every time a node is removed. Without network management messages being handled efficiently, the control network may fail.

Transmissions containing data important for the control of the process should also be high priority. Applications running in various stations in the network may be using control variables for various purposes. Some of these control variables may be collected outside the station doing the calculations and therefore must be transmitted across the control network. The control variables may be updated synchronously or asynchronously. In any case, this data is very important in keeping the process under control and must be delivered in a timely fashion.

Priority level 4 is used for messages relating to control data and network management. Besides the alarm messages being transmitted at level 6, the control and network management transmissions will be the highest priority transmissions on the control network. This makes sense, since these messages are the backbone of the control process. Since the number of alarm messages being transmitted is expected to be very small (system malfunctions should be infrequent), control data and network maintenance will usually be the highest priority data present on the control network.

2.4.3. Routine Data

Network traffic categorized as routine encompasses transmissions that are important to the control process, but not as time critical as control data or network management data. An example of this would be network traffic associated with console displays. Operators may attempt to display various pieces of data on a display device. Doing so usually means collecting data from other stations in the control network that are responsible
for maintaining the displayed variables. Therefore, this data must be sent across the control network to stations with display devices. Furthermore, the display must be updated as values in the control network change. This means that a periodic flow of data to the station housing the display must occur. In other words, the data on the display will be updated at some predetermined periodic rate.

Another example of an application that would rely on transmissions of this priority may be a historical device. This would be a station on the control network responsible for collecting data on various control variables throughout the network. An operator could examine the trends in the data, at his convenience, and find possible faults or improvements that could be made to the control process. This information is not critical to maintaining the process, but must still be delivered close to the sampling rate of the historical device to maintain validity of any statistical analysis that may be done.

Priority level 2 is used for messages related to routine data. This data is not as time critical as level 6 and 4 transmissions, but should still be given priority over the operations described in the next section.

2.4.4. File Transfer

The lowest priority traffic on the control network is associated with file transfer. File transfers occur when a node on the control network is booted. Many nodes do not contain any external storage devices to load their software into memory. Instead, they are installed with boot PROMs that allow for download across the control network from a server node containing all the software. This type of transfer is associated with large frames over the time it takes to complete the download. A transfer such as this at a high
priority level could endanger the control process, because control data may not be transmitted before their hard deadlines.

Priority level 0 is used for messages related to file transfer. The amount of time it takes to download a node over the control network is not as important as maintaining the process being controlled.

2.5. Analyzing Utilization and Throughput

The utilization and queuing delay of network traffic associated with a particular priority level is mathematically modelled in this section. These models will represent the functional descriptions of each priority level already given. Before this can be done, however, some mathematical foundation must be discussed. The model presented is taken from [5]. This model will be used as a base to build other models, specifically the model of the buffer insertion protocol presented later. This will allow the two protocols to be easily compared.

2.5.1. General Terms

Before explaining the details of the model, some background terminology must be presented. Utilization, $U$, is the fraction of time data frames are transmitted onto the control network. Throughput, $S$, is the total number of data bits received at a destination per second expressed as a fraction of the bandwidth. These terms can be used to discuss network wide trends concerning all stations on the control network, as well as specific stations. $U_i$ and $S_i$ are the utilization and throughput of priority level $i$, where $i$ is equal to 0, 2, 4, or 6. The relationship between $S$ and $U$ is given by
\[ S_i = \alpha_i U_i \]

where

\[ \alpha_i = \frac{T_i}{(T_i + T_{oh})} \]

\( T_i \) is the mean frame length of priority level \( i \) transmissions. If transmission time is measured in bit times, or the amount of time it takes to transmit one bit, then \( T_i \) is also the transmission time of priority level \( i \) frames. For example, a 5 byte frame will take 40 bit times to transmit. The mean length of a frame does not include any header or trailer information. \( T_{oh} \) is the number of overhead bits in a frame. This value is the same for all priority levels. It is also the time it takes to transmit the overhead portion of any frame. Figure 2 portrays a typical frame format, showing the header, trailer, and data portions of the frame.

<table>
<thead>
<tr>
<th>PREAMBLE</th>
<th>SD</th>
<th>FC</th>
<th>DA</th>
<th>SA</th>
<th>DATA</th>
<th>FCS</th>
<th>ED</th>
</tr>
</thead>
</table>

Figure 2 - The frame format of the IEEE 802.4 MAC sublayer is made up of 12 to 14 bytes of overhead. This is due to the preamble which can be 1, 2, or 3 bytes depending on the capacity of the bus. The data field may contain anywhere from 0 to 1014 bytes of information.

The frame overhead consists of the preamble, start delimiter (SD), frame control (FC), destination address (DA), source address (SA), frame check sequence (FCS), and end delimiter (ED). The start delimiter, frame control, and end delimiter are one byte fields. The destination address and source address are two byte fields. The frame check sequence is a three byte field. The preamble is 1, 2, or 3 bytes depending on whether the
capacity of the bus is 1, 5 or 10 Mbits/sec respectively. The specific meaning of each field is not important for this analysis. It is just important to note that these fields are what make up the variable $T_{eh}$. The data field in Figure 2 changes size depending on how much information an application has to transmit. It may be 0 to 1014 bytes in size.

$\alpha_i$ is a factor relating the data portion of a frame to the overall size of the frame, including the headers and trailers. From the earlier equation, the difference between throughput and utilization is evident. Utilization is a measure of the total frames transmitted. Throughput is a measure of the data received, excluding overhead.

Another metric that is used to evaluate the state of a network is the offered load. The offered load, $G$, is the number of data bits generated by all active stations per second expressed as a fraction of the channel bandwidth. More simply, it is the amount of data generated, by all nodes, for transmission, over a given time. If the network can handle the amount of data being generated for transmission, then the offered load will equal the utilization. If the network cannot handle the amount of data being generated for transmission, then the offered load will be greater than the utilization. Like utilization and throughput, $G_i$ represents the offered load for priority level $i$ transmissions. $G'_i$ is the offered load of priority level $i$ when the offered load is considered to be all of the bits generated per unit time, not just the data bits. In other words, $U_i$ is to $G'_i$ as $S_i$ is to $G_r$.

$T$, represents the mean token passing time between two stations on the logical ring. This time includes the station delay, the head-end delay, the transmitter and receiver modem delays, the token transmission time, and the propagation delay. If, for example, there are $N$ stations on the ring, then $NT$, would be the minimum amount of time
needed for the token to circulate the entire network. This minimum token rotation time occurs if no station on the ring transmits any data. The minimum token rotation time is represented by \( C_0 \). \( C \) represents the mean token rotation time. This is the mean time between the token arriving at a particular access class, and returning to the same class.

Time values associated with the high priority token hold time are represented by the symbol \( T_r \). Similarly, the target rotation times for access classes 4, 2, and 0 are represented by the variables \( T_R(4) \), \( T_R(2) \), and \( T_R(0) \) respectively. Lastly, \( T_m(i) \) represents the amount of time access class \( i \) holds the token after its high priority token hold timer or target rotation timer has expired. Remember that as long as a transmission begins before the timer expires, it will always complete. For example, the value of \( T_m(6) \) ranges from 0 to the transmission time of the maximum sized frame, depending on when the high priority token hold timer expires.

2.5.2. Assumptions

As with any mathematical model, certain simplifying assumptions need to be made to keep the model tractable. The following are assumptions made for the model being presented.

- error free operation of the network
- no additions or deletions of nodes from a running system
- a large number of nodes
- the target rotation times are greater than the minimum token rotation time
- the target rotation times are well separated and decrease with decreasing priority.

These assumptions will become clearer as the model is presented. A large number of nodes must be used because the model being presented is based upon the mean to-
ken rotation time of the network. For the model to be precise, the actual token rotation
time must remain very close to the mean token rotation time. This is accomplished when
a large number of nodes exist in the system.

Target rotation times must be separated by many bit times so that the utilization
and throughput given by the model is clear for a particular priority level. Target rotation
times too close will result in utilizations that are a combination of two or more priority
levels.

2.5.3. **Lower Priority Levels**

The utilization models of the lower priority levels are discussed first. These mod-
els represent the utilizations of level 4, level 2, and level 0 transmissions. These are pres-
ented first since they are more intuitive and therefore easier to understand than the model
representing the utilization characteristics of access class 6.

Normally the target rotation timers of each access class are configured so that
\[ T_R(0) < T_R(2) < T_R(4). \]  
This, however, does not have to be the case. The timers may be
configured so that any access class is greater or less than any other. The only criteria be-
ing that they are well separated. For the following discussion, we will assume that \( T_R(0) \)< \( T_R(2) \)< \( T_R(4). \)

2.5.3.1. **Peak Utilizations**

Examining each priority level separately, it is easy to see that the utilization of a
particular priority level increases as the offered load of that priority level increases. This
will occur until the mean token rotation time exceeds the target rotation time for that ac-
cess class. Assuming, for a moment, that all network traffic is comprised of a single
priority level, \( i \), and that the token rotation time is equal to the target rotation time for that priority level, then the utilization is at its maximum and is given by

\[
P_i = \frac{T_R(i) - C_o}{T_R(i)}
\]

where \( i \) represents the priority level of 4, 2, or 0, again where \( C_o \) is the minimum token rotation timer, and \( P \) represents the peak utilization of priority level \( i \). Any wasted bandwidth is because of the overhead involved with passing the token, otherwise, all of the bandwidth available to priority level \( i \) is being used.

Continuing the assumption that all network traffic is being made up of a single lower priority level, the following statement about utilization may be made. The utilization of a priority level must be the minimum of the offered load of that priority level, and the peak utilization of that priority level. In other words,

\[
U_i = \text{MIN} \left( G_i, P_i \right)
\]

if network traffic is made up of only access class \( i \) transmissions.

### 2.5.3.2. Actual Utilizations

The previous section explained what happens to the utilizations of the lower priority access classes when all network traffic belongs to a single priority level. However, the network usually has a mixture of many different priority levels being transmitted in a single token rotation. Network traffic of a higher priority level will use bandwidth that would otherwise be available to lower priority transmissions. For example, when the mean token rotation time increases above the level 4 target rotation time, the level 4 utilization becomes dependent on the utilization of the higher priority level (level 6) and the token rotation time of an idle bus. Therefore, when the token rotation time reaches
the target rotation time of a particular priority level, the utilization for that priority level will have reached a local maximum for that particular combination of offered loads. Only when network traffic consists of the priority level in question is when the utilization of the priority level reaches its peak described in the previous section. Therefore, the utilization when the mean token rotation time equals the target rotation time of a particular priority level will always be the minimum of the offered load of that priority level and the peak utilization of that priority level minus the combined utilizations of the higher priority levels. Note that the utilization at any priority level can never become less than zero. If the utilization from a higher priority level uses all of a particular priority level's bandwidth then the utilization for that priority level remains zero and does not go negative. It should also be noted here that network traffic of a lower priority level cannot reduce the utilization of a higher priority level. The lower priority levels have smaller target rotation times and cannot drive the mean token rotation time above the target rotation time of the priority level in question.

Whenever the mean token rotation time is smaller than the target rotation time for a particular priority level, there is bandwidth available to handle the offered load of that priority level. More formally,

\[
U_4 = \begin{cases} 
G_4, & \bar{C} < T_R(4) \\
\text{MAX} \left(0, \ P_4 - U_6\right), & \bar{C} \geq T_R(4)
\end{cases}
\]
\[
U_2 = \begin{cases} 
G_2, & \overline{C} < T_R(2) \\
\text{MAX} (0, P_2 - U_6 - U_4), & \overline{C} \geq T_R(2)
\end{cases},
\]

and

\[
U_0 = \begin{cases} 
G_0, & \overline{C} < T_R(0) \\
\text{MAX} (0, P_0 - U_6 - U_4 - U_2), & \overline{C} \geq T_R(0)
\end{cases}.
\]

Calculating these three utilizations still requires that the mean token rotation time be known. At least when represented in this form it does. It may also be expressed in the following notation.

\[
U_4 = \text{MAX} (\text{MIN} (G_4, P_4 - U_6), 0)
\]

\[
U_2 = \text{MAX} (\text{MIN} (G_2, P_4 - U_6 - U_4), 0)
\]

\[
U_0 = \text{MAX} (\text{MIN} (G_0, P_4 - U_6 - U_4 - U_2), 0).
\]

Notice that each of the lower priority level utilizations may now be calculated if the offered load, target rotation time, minimum token rotation time, and high priority utilization is known. All of these factors have already been expressed except one, the level 6 utilization. Without it, none of the other utilizations may be computed. The next section is dedicated to explaining the mathematical model associated with computing the level 6 utilization.
2.5.4. High Priority

Expressing the level 6 utilization mathematically is more difficult than expressing the utilizations of the lower priority levels. This is mainly due to the fact that the high priority token hold timer is used differently than the target rotation timers of the lower priority levels. The target rotation timers indicated the maximum amount of time access classes of a particular priority level may transmit in a single token rotation. The high priority token hold timer doesn't give the maximum token rotation time if only level 6 frames are being transmitted. Instead, it gives the amount of time each station on the network may transmit level 6 data. This section explains how the level 6 utilization can be expressed in terms of target rotation times, offered loads, etc., so that it may be used to solve the equations of lower priority utilization. Note that it makes no sense to model the level 6 utilization in terms of the level 4, 2, or 0 utilizations since the goal is to use the result here to resolve the final variable in those equations.

2.5.4.1. Deriving the Peak Level 6 Utilization

As stated above, the high priority token hold timer does not express the maximum token rotation time for transmitting only level 6 data as does the target rotation timers. However, the maximum token rotation time, if network traffic is only made up of level 6 data, can be expressed in terms of the high priority token hold time as follows;

\[ C_s = (T_s + T_m(6) + T_i)N. \]

where \( N \) is the number of stations on the network, \( T_s \) is the high priority token hold time, \( T_m(6) \) is the maximum overshoot for a priority level 6 access class, and \( T_i \) is the token passing time between two adjacent stations.
To achieve maximum level 6 utilization, each of the $N$ stations on the network must transmit for their entire high priority token hold time, plus some additional transmission time to finish up once the timer expires. Each station must also pass the token to the next device.

Again, assuming that network traffic is made up of only level 6 transmissions, the peak utilization of priority level 6 is given by

$$P_6 = \frac{C_s - C_0}{C_s}.$$ 

Since it is known that $C_0 = NT_\rho$, the expression is equivalent to

$$P_6 = \frac{[T_s + T_m(6)]N}{C_s}.$$ 

### 2.5.4.2. Deriving the General Level 6 Utilization

Depending on how the value of the maximum level 6 token rotation time, $C_s$, compares to the target rotation times, the actual level 6 utilization may be simple or very difficult to model. Unlike the target rotation timers of the lower priority levels, $C_s$ depends upon the number of stations in the network. It also depends upon the mean size of level 6 transmissions, but to a much lesser extent. It is possible that the maximum level 6 token rotation time, $C_s$, fall anywhere in the range of target rotation timers depending on the value of the high priority token hold time and the number of stations in the network. For any timer configuration, one of the following conditions will exist

1. $T_R(0) < T_R(2) < T_R(4) < C_s$
2. $T_R(0) < T_R(2) < C_s < T_R(4)$
3. $T_R(0) < C_s < T_R(2) < T_R(4)$
4. \( C_s < T_R(0) < T_R(2) < T_R(4) \).

The level 6 utilization for each of these cases is different. Each case is treated separately in one of the next four sections.

Before proceeding, some general conclusions about level 6 utilization will be drawn, as was done for the lower level utilizations in the preceding sections. This will be used as a basis for the level 6 utilization models.

The equation for the level 6 peak utilization only applies when the network traffic consists of strictly level 6 transmissions. The fact that the level 6 utilization falls between the offered load and the peak utilization under these same constraints has also been discussed. These models were developed based on the premise that the mean token rotation time did not exceed \( C_s \). However, if network traffic consists of transmissions from many priority levels, the mean token rotation time may exceed \( C_s \) in three out of the four cases listed above. Therefore, the level 6 utilization under mixed network traffic should not be dependent upon the value of \( C_s \), but rather on the mean token rotation time. It may be stated that

\[
U_6 = \text{MIN} \left( G'_6, \frac{\left[ T_s + T_m(6) \right] N}{C} \right).
\]

In general, the level 6 utilization will be the minimum of the level 6 offered load and the maximum level 6 transmission time divided by mean token rotation time.

2.5.4.2.1. Case 1: \( T_R(0) < T_R(2) < T_R(4) < C_s \)

The case when all of the target rotation times are smaller than \( C_s \) is the easiest to model. To fully analyze the level 6 utilization when \( C_s \) is greater than all of the target rotation times the model must be broken into two sub-cases. These sub-cases are
1. $\bar{C} = C_s$, the mean token rotation time is equal to the level 6 token rotation time.

2. $\bar{C} < C_s$, the mean token rotation time is less than the level 6 token rotation time.

2.5.4.2.1.1. Case 1a: $\bar{C} = C_s$

When the mean token rotation reaches $C_s$, the utilization of all lower priority levels will be driven to 0. In other words, level 6 traffic is capable of increasing the mean token rotation time so that no other priority level transmission takes place. This means that the lower priority levels cannot have an affect on the utilization of priority level 6, and that the maximum level 6 utilization is actually the peak level 6 utilization, $P_6$.

A more formal proof of this derivation follows.

*Theorem*: if $\bar{C} = C_s$ and $T_R(0) < T_R(2) < T_R(4) < C_s$ then $U_6 = P_6$

*Proof*:

1. $U_6 = \text{MIN} \left( G'_6, \frac{[T_s+T_m(6)]N}{C} \right)$ definition of $U_6$

2. $P_6 = \frac{[T_s+T_m(6)]N}{C_s}$ definition of $P_6$

3. $P_6 = \frac{[T_s+T_m(6)]N}{C}$

4. if $\bar{C} = C_s$ then $G'_6 \geq \frac{[T_s+T_m(6)]N}{C}$ from (1)

5. $U_6 = \frac{[T_s+T_m(6)]N}{C}$ from (1) and (4)

6. $U_6 = P_6$ from (3) and (5)
2.5.4.2.1.2. Case 1b: $\overline{C} < C_s$

When the mean token rotation time is less than the level 6 token rotation time, bandwidth still exists for more level 6 transmissions to take place in a single token rotation. Therefore, the level 6 utilization must be equal to the level 6 offered load.

Theorem: if $\overline{C} < C_s$ and $T_R(0) < T_R(2) < T_R(4) < C_s$ then $U_6 = G'_6$

Proof:

1. $U_6 = MIN \left( G'_6, \frac{[T + T_m(6)]N}{\overline{C}} \right)$ definition of $U_6$
2. if $\overline{C} < C_s$ then $G'_6 < \frac{[T + T_m(6)]N}{\overline{C}}$
3. $U_6 = G'_6$ from (1) and (2)

2.5.4.2.1.3. Level 6 Utilization Model for Case 1

The entire level 6 utilization model when the level 6 maximum token rotation time is greater than all of the target rotation times can be stated as follows,

\[ \text{if } \overline{C} = C_s \text{ then } U_6 = MIN \left( G'_6, P_6 \right) \]

\[ \text{else } U_6 = G'_6. \]

This reduces to

\[ U_6 = MIN \left( G'_6, P_6 \right) \]

since the else condition is already a subset of the first condition.

2.5.4.2.2. Case 2: $T_R(0) < T_R(2) < C_s < T_R(4)$

This section develops a model for level 6 utilization when the maximum token rotation time for level 6 traffic is less than the target rotation time of priority level 4. $C_s$ is no longer the maximum token rotation time of the entire network. Instead, the value
of the level 4 target rotation time is the maximum token rotation time possible. This means that bandwidth will still be available for level 4 transmissions after level 6 traffic has reached its peak. Additional level 4 traffic will decrease the utilization of priority level 6. In other words, once the mean token rotation time grows greater than $C_s$, the maximum level 6 utilization becomes dependent upon the target rotation time of priority level 4. As the additional level 4 traffic pushes the mean token rotation greater than $C_s$, the level 6 utilization decreases. If the mean token rotation time is less than $C_s$ then level 4 traffic has no effect on level 6 utilization.

To examine the level 6 utilization, the model must be broken into three cases.

1. $\bar{C} = TR(4)$, the mean token rotation time is equal to the level 4 target rotation time.

2. $C_s \leq \bar{C} < TR(4)$, the mean token rotation time is less than the target rotation time and greater than or equal to the level 6 token rotation time.

3. $\bar{C} < C_s$, the mean token rotation time is less then the level 6 token rotation time.

2.5.4.2.2.1. Case 2a: $\bar{C} = TR(4)$

When the mean token rotation time equals the level 4 target rotation time, the mean token rotation time has reached its maximum value. The level 6 utilization, under these circumstances, is dependent upon the level 4 target rotation time. The maximum level 6 utilization will still occur when all $N$ stations on the control network are transmitting level 6 data for there entire high priority token hold times, but the mean token rotation time will be greater than $C_s$. Mathematically stated,

$$H_4 = \left[ \frac{T_s + T_m(6)}{TR(4)} \right] N,$$
where $H_4$ is the maximum level 6 utilization possible when the mean token rotation is equal to the level 4 target rotation time, and both are greater than $C_s$.

If the maximum amount of level 6 data has not been transmitted, then the level 6 utilization is equal to the offered load of priority level 6. The level 6 utilization can now be stated as follows,

$$U_6 = \text{MIN} \left( G_6', H_4 \right).$$

A formal proof follows.

**Theorem:**

If $C = T_R(4)$ and $T_R(0) < T_R(2) < C_s < T_R(4)$ then $U_6 = \text{MIN} \left( G_6', H_4 \right)$

**Proof:**

1. $\overline{C} = T_R(4)$ given

2. $U_6 = \text{MIN} \left( G_6', \frac{[T_r + T_m(6)]N}{\overline{C}} \right)$ definition of $U_6$

3. if $G_6' \leq \frac{[T_r + T_m(6)]N}{\overline{C}}$ then $U_6 = G_6'$ from (2)

4. if $G_6' > \frac{[T_r + T_m(6)]N}{\overline{C}}$ then $U_6 = \frac{[T_r + T_m(6)]N}{T_R(4)}$ from (2)

5. $U_6 = \frac{[T_r + T_m(6)]N}{T_R(4)}$ substitute (1) into (4)

6. $H_4 = U_6$

7. $U_6 = \text{MIN} \left( G_6', H_4 \right)$ from (3), (5), and (6)

2.5.4.2.2.2. **Case 2b: $C_s \leq \overline{C} < T_R(4)$**

When the mean token rotation time falls between the level 4 target rotation time and the level 6 token rotation time, the total utilization of the system can no longer be represented by $P_4$, even though it still consists of only level 4 and level 6 traffic. The
maximum level 6 utilization must still be represented in terms of the level 4 traffic load. In other words, the level 6 utilization is the fraction of the peak utilization that is not diminished by level 4 traffic. Since network traffic is made up of only level 4 and level 6 transmissions, $1 - G_4'$ represents the fraction of utilization that is not made up of level 4 traffic. Therefore,

$$U_6 = MIN \left( G_6', P_6(1 - G_4') \right)$$

represents the level 6 utilization for this specific circumstance.

A formal proof of the level 6 utilization follows.

**Theorem:**

if $C_s \leq \bar{C} < T_R(4)$ and $T_R(0) < T_R(2) < C_s < T_R(4)$ then

$$U_6 = MIN \left( G_6', P_6(1 - G_4') \right)$$

**Proof:**

1. if $\bar{C} < T_R(4)$ then $U_4 = G_4'$
2. $U_6 = MIN \left( G_6', \frac{[T_R + T_m(6)]N}{c} \right)$ definition of $U_6$
3. if $G_6' \leq \frac{[T_R + T_m(6)]N}{c}$ then $U_6 = G_6'$ from (1)
4. if $G_6 > \frac{[T_R + T_m(6)]N}{c}$ then $U_6 = \frac{[T_R + T_m(6)]N}{c}$ from (1)
5. $U = U_4 + U_6$
6. $U = G_4' + \frac{[T_R + T_m(6)]N}{c}$ substitute (1) and (4) into (5)
7. $U = \frac{\bar{C} - C_o}{c}$ definition of utilization
8. $1 - G_4' = \frac{C_o + [T_R + T_m(6)]N}{c}$ substitute (6) into (7)
9. $C_o = NT_t$ definition of minimum token rotation time
10. $1 - G_4' = \frac{[T_R + T_m(6) + T_t]N}{c}$ substitute (9) into (8)

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11. \( C_s = (T_s + T_m(6) + T_i)N \) definition of \( C_s \)
12. \( 1 - G'_4 = \frac{C_s}{C} \) substitute (11) into (10)
13. \( P_6 = \frac{C_r-C_6}{C_s} \) definition of \( P_6 \)
14. \( P_6 = \frac{C_r-C_6}{C_s(1-G'_4)} \) substitute (12) into (13)
15. \( P_6(1 - G'_4) = \frac{C_r-C_s}{C} \) simplify (14)
16. \( P_6(1 - G'_4) = U_6 \) from (4), (9), (11), and (14)
17. \( U_6 = \text{MIN} \left( G'_6, P_6(1 - G4') \right) \) from (3) and (16)

2.5.4.2.2.3. Case 2c: \( \bar{C} < C_s \)

Whenever the mean token rotation time is less than the level 6 maximum token rotation time, the entire level 6 offered load may be handled. Therefore,

\[ U_6 = G'_6. \]

2.5.4.2.2.4. Level 6 Utilization Model for Case 2

The entire level 6 utilization model when the level 6 maximum token rotation time is less than the level 0 and level 2 target rotation times, and less than the level 4 target rotation time, can now be stated completely.

\[
\begin{align*}
\text{if } \bar{C} = T_R(4) \text{ then } U_6 &= \text{MIN} \left( G'_6, H_4 \right) \\
\text{else if } C_s \leq \bar{C} < T_R(4) \text{ then } U_6 &= \text{MIN} \left( G'_6, P_6(1 - G'_4) \right) \\
\text{else if } \bar{C} < C_s \text{ then } U_6 &= G'_6
\end{align*}
\]

The three conditions for level 6 utilization may also be expressed in terms of utilizations, instead of token rotation times. This is done for each of the three conditionals and the revised model is presented below.
When the mean token rotation time equals the level 4 target rotation time, the offered load of level 4 must be greater than the utilization of level 4. Also, the total utilization of the system must be equal to \( P_\ell \). This is not to say that the entire utilization is made up of level 4 traffic. In fact it is not, it is made up of level 4 and level 6 traffic only. The utilizations of priority level 0 and level 2 are 0 because the mean token rotation time is greater than there respective target rotation times. Therefore, saying that the level 4 offered load and the level 6 utilization is greater than the level 4 peak utilization is equivalent to stating that the mean token rotation time equals that level 4 target rotation time.

\[
[ G_4' + \text{MIN} \left( G_6', H_4 \right) \geq P_4 ] \equiv \left[ C_s = \bar{C} \text{ and } T_R(0) < T_R(2) < C_s < T_R(4) \right]
\]

If the level 4 offered load and level 6 utilization are not great enough to exceed the peak utilization, then perhaps the level 4 and level 6 traffic are greater than the level 6 maximum token rotation time. This would mean that the level 4 and level 6 offered loads exceeded the level 6 peak utilization. More formally stated,

\[
[ G_4' + G_6' \geq P_6 ] \equiv [ C_s \leq \bar{C} < T_R(4) \text{ and } T_R(0) < T_R(2) < C_s < T_R(4) ].
\]

Lastly, if both of the previous conditions cannot be satisfied, then the mean token rotation time must be less than \( C_s \). The entire model may now be restated as follows.

\[
\text{if} \left[ G_4' + \text{MIN} \left( G_6', H_4 \right) \geq P_4 \right] \text{ then }
\]

\[
U_6 = \text{MIN} \left( G_6', H_4 \right)
\]

\[
\text{else if} \left[ G_4' + G_6' \geq P_6 \right] \text{ then }
\]

\[
U_6 = \text{MIN} \left( G_6', P_6(1 - G_4') \right)
\]

\[
\text{else }
\]

\[
U_6 = G_6'
\]

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2.5.4.2.3. **Case 3:** \( T_R(0) < C_s < T_R(2) < T_R(4) \)

This section discusses the characteristics of level 6 utilization when \( C_s \) is less than the target rotation time for level 2, and greater than the target rotation time of level 0. The argument used in the preceding section, when \( C_s \) fell between the target rotation times of level 4 and level 2, can be extended for this situation.

In the preceding section, to fully analyze the level 6 utilization, the problem had to be broken down into three cases with respect to the mean token rotation time. This approach can be followed when \( C_s \) falls between the target rotation times of level 2 and level 0 as well. The equations for level 6 utilization derived for the previous case will also apply here, since a portion of this derivation overlaps the previous derivation.

When the level 6 token rotation time falls between the level 2 and level 0 target rotation times, the derivations for the level 6 utilization model may be broken into five distinct cases based on the mean token rotation time. These cases are

1. \( \bar{C} = T_R(4) \), the mean token rotation time equals the level 4 target rotation time.
2. \( T_R(2) < \bar{C} < T_R(4) \), the mean token rotation time is less than the level 4 target rotation time and greater than the level 2 target rotation time.
3. \( \bar{C} = T_R(2) \), the mean token rotation time equals the level 2 target rotation time.
4. \( C_s \leq \bar{C} < T_R(2) \), the mean token rotation time is less than the level 2 target rotation time and greater than or equal to the level 6 token rotation time.
5. \( \bar{C} < C_s \), the mean token rotation time is less than the level 6 target rotation time.

Notice that case 1 and case 5 for this level 6 utilization analysis are identical to the level 6 utilization analysis when the level 6 token rotation time fell between the level
4 and level 2 target rotation times. This means that two of the five cases outlined above have already been solved. The models for these two cases will be repeated for completeness. However, for a full understanding of the derivation the previous sections should be examined.

2.5.4.2.3.1. Case 3a: $\overline{C} = T_R(4)$

The level 6 utilization under these circumstances is equivalent to the derivation done in section 1.5.4.2.2.1. This can be stated since the following three criteria are the same for both cases.

1. The mean token rotation time is equal to the level 4 target rotation time.
2. The mean token rotation time is greater than $C_r$.
3. The level 4 target rotation time is greater than the level 0 and level 2 target rotation times.

It is irrelevant that the level 6 maximum token rotation time falls between the level 0 and level 2 target rotation times, instead of the level 2 and level 4 target rotation times. The result is presented here for completeness.

$$U_6 = MIN \left(G'_6, H_4 \right)$$

2.5.4.2.3.2. Case 3b: $T_R(2) < \overline{C} < T_R(4)$

When the mean token rotation time is greater than the level 2 and level 0 target rotation times, the utilization for these priority levels will be 0. Therefore, the mean token rotation time is caused by network traffic from the level 4 and level 6 priority levels only. Note that the network traffic must consist of transmissions from both priority
classes, or just from level 4. Level 6 traffic alone cannot increase the mean token rotation time above the level 2 target rotation time.

When the offered load of priority level 6 is less than the maximum allowable bandwidth, then the level 6 utilization is equal to the level 6 offered load. However, when level 6 transmissions reach their maximum, that is to say, when all stations on the network are transmitting for their full high priority token hold time, the level 6 utilization may dwindle due to an increasing load of level 4 transmissions. Therefore, it can be said that the level 6 utilization under these circumstances is a fraction of the level 6 peak utilization. More specifically,

\[ U_6 = P_6(1 - G'_4). \]

Notice that as the level 4 offered load reaches the point where it becomes the total utilization of the network, the level 6 utilization drops to 0. This has to be the case since level 6 transmissions are guaranteed at each node for the high priority token hold time.

Also note that as the level 4 offered load drops to 0, the level 6 utilization approaches the peak utilization. The level 6 utilization will never reach its peak value, however, since a level 4 offered load must be present to increase the mean token rotation time above the level 2 target rotation time.

The level 6 utilization can now be presented as follows,

\[ U_6 = \text{MIN} \left( G'_6, P_6(1 - G'_4) \right). \]

Notice that this expression for level 6 utilization is identical to the expression for level 6 utilization derived in section 1.5.4.2.2.2. For that derivation, the mean token rotation time was greater than or equal to \( C_s \), and less than the level 4 target rotation time. The same is true for this derivation, except that the mean token rotation time can never equal
The fact that $C_r$ was greater than the level 2 target rotation for the derivation in section 1.5.4.2.2.2, and less than the level 2 target rotation time for this derivation is irrelevant. The derivation is done on the foundation that the mean token rotation time is less than the level 4 target rotation time, and greater than $C_r$. The proof from section 1.5.4.2.2.2 is therefore identical for this derivation and is not repeated.

2.5.4.2.3.3. Case 3c: $\overline{C} = T_R(2)$

The derivation of the level 6 utilization when the mean token rotation time equals the level 2 target rotation time is very similar to the derivation of level 6 utilization when the mean token rotation time equaled the level 4 target rotation time. This derivation was done in section 1.5.4.2.2.1.

When the mean token rotation time equals the level 2 target rotation time, the mean token rotation time has reached its maximum value. The level 6 utilization, under these circumstances, is dependent upon the level 2 target rotation time. The maximum level 6 utilization will still occur when all $N$ stations on the control network are transmitting level 6 data for their entire high priority token hold times, but the mean token rotation time will be greater than $C_r$. Mathematically stated,

$$H_2 = \frac{[T_s + T_m(6)]N}{T_R(2)},$$

where $H_2$ is the maximum level 6 utilization possible when the mean token rotation is equal to the level 2 target rotation time, and both are greater than $C_r$.

If the maximum amount of level 6 data has not been transmitted, then the level 6 utilization is equal to the offered load of priority level 6. The level 6 utilization can now
be stated as follows,

\[ U_6 = \text{MIN} \left( G'_6, H_2 \right) \]

The proof for this expression of level 6 utilization is identical to the proof for the case of the mean token rotation time equaling the level 4 target rotation time. The only difference is that the level 2 target rotation time, \( T_R(2) \), should be substituted for the level 4 target rotation time, \( T_R(4) \), throughout the proof.

2.5.4.2.3.4. Case 3d: \( C_s \leq C < T_R(2) \)

When the mean token rotation time falls between the level 2 target rotation time and the level 6 token rotation time, the total utilization of the system can no longer be represented by \( P_2 \). For this case, the level 6 utilization is the fraction of the level 6 peak utilization that is not diminished by level 4 and level 2 traffic. Since network traffic is made up level 2, level 4 and level 6 transmissions, \( P_6(1 - G'_2 - G'_4) \) represents the fraction of level 6 utilization that is not made up of level 2 or level 4 traffic. Therefore,

\[ U_6 = \text{MIN} \left( G'_6, P_6(1 - G'_2 - G'_4) \right) \]

represents the level 6 utilization for this specific circumstance.

The proof for this expression of level 6 utilization is identical to the proof in section 1.5.4.2.2.2. The only difference is that the total utilization is equal to the combination of level 2, level 4, and level 6 utilizations instead of just level 4 and level 6. The reason being that the mean token rotation time falls between the level 2 target rotation time and \( C_s \) instead of the level 4 target rotation time and \( C_r \). This means that level 2 traffic may be transmitted. Note that since the mean token rotation time is less than the
level 2 target rotation time, the level 2 and level 4 utilizations are equal to their respective offered loads.

2.5.4.2.3.5. Case 3e: $\bar{C} < C_s$

Whenever the mean token rotation time is less than the level 6 maximum token rotation time, the entire level 6 offered load may be handled. Therefore,

$$U_6 = G'_6$$

2.5.4.2.3.6. Level 6 Utilization Model for Case 3

The entire level 6 utilization model when the level 6 maximum token rotation time is greater than the level 0 target rotation time, and less than the level 2 and level 4 target rotation times, can now be stated completely.

$$\text{if } \bar{C} = T_R(4) \text{ then } U_6 = \text{MIN} \left( G'_6, H_4 \right)$$

$$\text{else if } T_R(2) < \bar{C} < T_R(4) \text{ then } U_6 = \text{MIN} \left( G'_6, P_6(1 - G'_4) \right)$$

$$\text{else if } \bar{C} = T_R(2) \text{ then } U_6 = \text{MIN} \left( G'_6, H_2 \right)$$

$$\text{else if } C_s \leq \bar{C} < T_R(2) \text{ then } U_6 = \text{MIN} \left( G'_6, P_6(1 - G_2' - G'_4) \right)$$

$$\text{else if } \bar{C} < C_s \text{ then } U_6 = G'_6$$

The five conditions for level 6 utilization may also be expressed in terms of utilizations, instead of the mean token rotation time and target rotation times. This is done for each of the conditionals statements and the revised model is presented below.

The first conditional statement, that the mean token rotation time is equal to the level 4 target rotation time, is equivalent to stating that the level 4 offered load and level 6 utilization are greater than the peak level 4 utilization for the same reasons stated in section 2.5.4.2.2.4.
Stating that the mean token rotation time is greater than the level 2 target rotation time, but less than the level 4 target rotation time, is equivalent to saying that the total network utilization is greater than the level 2 peak utilization, since the peak utilization only occurs when the mean token rotation time equals the level 2 target rotation time. The total network utilization consists of the level 4 offered load and the level 6 utilization. More formally stated,

\[ G_4' + \text{MIN}(G_6', P_6(1 - G_4')) \geq P_2 \] \iff \[ T_R(2) < \bar{C} < T_R(4) \].

When the mean token rotation time is equal to the target rotation time of level 2, the offered load of level 2 must be greater than the utilization of level 2. Also, the total utilization of the system must be equal to \( P_2 \). This is not to say that the entire utilization is made up of level 2 traffic. In fact it is not, it is made up of level 2, level 4, and level 6 traffic. The utilization of priority level 0 is 0 because the mean token rotation time is greater than its target rotation time. Therefore, saying that the mean token rotation time equals the level 2 target rotation time is equivalent to saying that the level 2 offered load plus the level 4 and level 6 utilizations is greater than the peak level 2 utilization. Since the mean token rotation time is less than the level 4 target rotation time, the level 4 utilization is equal to the level 4 offered load. More formally stated

\[ G_2' + G_4' + \text{MIN}(G_6', H_2) \geq P_4 \] \iff \[ \bar{C} = T_R(2) \].

For the mean token rotation time to be greater than or equal to \( C_c \), and less than the level 2 target rotation time, the offered loads of level 2 and level 4, combined with the level 6 utilization, must exceed the peak utilization of level 6. Only these offered loads are considered since they are the only levels that contribute to the total utilization.
for a mean token rotation time in this range. More formally stated,

\[
\left[ \left[ G'_2 + G'_4 + \min \left( G'_6, P_6(1 - G'_2 - G'_4) \right) \right] \geq P_6 \right] \equiv \left[ C_s \leq \bar{C} < T_R(2) \right].
\]

Lastly, if both of the previous conditions cannot be satisfied, then the mean token rotation time must be less than \( C_s \). The entire model may now be restated as follows.

\[
\begin{align*}
& \text{if } \left[ G'_4 + \min \left( G'_6, H_4 \right) \geq P_4 \right] \text{ then} \\
& U_6 = \min \left( G'_6, H_4 \right) \\
& \text{else if } \left[ G'_4 + \min \left( G'_6, P_6(1 - G'_4) \right) \geq P_2 \right] \text{ then} \\
& U_6 = \min \left( G'_6, P_6(1 - G'_4) \right) \\
& \text{else if } \left[ G'_2 + G'_4 + \min \left( G'_6, P_6(1 - G'_2 - G'_4) \right) \geq P_6 \right] \text{ then} \\
& U_6 = \min \left( G'_6, P_6(1 - G'_2 - G'_4) \right) \\
& \text{else} \quad U_6 = G'_6
\end{align*}
\]

2.5.4.2.4. **Case 4:** \( C_s < T_R(0) < T_R(2) < T_R(4) \)

This section discusses the characteristics of level 6 utilization when \( C_s \) is less than all of the target rotation times. Once again, some of the results derived in preceding sections can be extended for this particular circumstance.

To fully analyze the level 6 utilization, the problem must again be broken down into individual cases with respect to the mean token rotation time. These cases are

1. \( \bar{C} = T_R(4) \), the mean token rotation time equals the level 4 target rotation time.
2. \( T_R(2) < \bar{C} < T_R(4) \), the mean token rotation time is less than the level 4 target rotation time and greater than the level 2 target rotation time.
3. \( \bar{C} = T_R(2) \), the mean token rotation time equals the level 2 target rotation time.
4. $T_R(0) < \bar{C} < T_R(2)$, the mean token rotation time is less than the level 2 target rotation time and greater than the level 0 target rotation time.

5. $\bar{C} = T_R(0)$, the mean token rotation time equals the level 0 target rotation time.

6. $Cs \leq \bar{C} < T_R(0)$, the mean token rotation time is less than the level 0 target rotation time and greater than or equal to the level 6 maximum token rotation time.

7. $\bar{C} < Cs$, the mean token rotation time is less than the level 6 target rotation time.

Note that cases 1, 2, 3, and 5 have had level 6 utilization models derived in previous sections. This means that four of the seven cases outlined above have already been solved. The level 6 utilization models derived for these cases will be stated for completeness. However, for a full understanding of the derivations, the previous sections should be examined.

2.5.4.2.4.1. Case 4a: $\bar{C} = T_R(4)$

The level 6 utilization under these circumstances is equivalent to the derivation done in section 1.5.4.2.2.1. This can be stated since the following three criteria are the same for both cases.

1. The mean token rotation time is equal to the level 4 target rotation time.

2. The mean token rotation time is greater than $Cs$.

3. The level 4 target rotation time is greater than the level 0 and level 2 target rotation times.

It is irrelevant that the level 6 maximum token rotation time is less than the level 0 target rotation time, instead of falling between the level 2 and level 4 target rotation times.
result is presented here for completeness.

\[ U_6 = \min \left( G'_6, H_4 \right) \]

2.5.4.2.4.2. Case 4b: \( T_R(2) < \bar{C} < T_R(4) \)

The level 6 utilization under these circumstances is equivalent to the derivation done in section 1.5.4.2.3.2. This can be stated since the following three criteria are the same for both cases.

1. The mean token rotation time is less than the level 4 target rotation time and greater than the level 2 target rotation time.
2. The mean token rotation time is greater than \( C_r \).
3. The level 4 target rotation time is greater than the level 0 and level 2 target rotation times.

It is irrelevant that the level 6 maximum token rotation time is less than the level 0 target rotation time, instead of falling between the level 2 and level 4 target rotation times. The result is presented here for completeness.

\[ U_6 = \min \left( G'_6, P_6(1 - G'_4) \right) \]

2.5.4.2.4.3. Case 4c: \( \bar{C} = T_R(2) \)

The level 6 utilization under these circumstances is equivalent to the derivation done in section 1.5.4.2.3.3. This can be stated since the following three criteria are the same for both cases.

1. The mean token rotation time is equal to the level 2 target rotation time.
2. The mean token rotation time is greater than \( C_r \).
3. The level 4 target rotation time is greater than the level 0 and level 2 target rotation times.
It is irrelevant that the level 6 maximum token rotation time is less than the level 0 target rotation time, instead of falling between the level 2 and level 4 target rotation times. The result is presented here for completeness.

\[ U_6 = \text{MIN} \left( G'_6, H_2 \right) \]

2.5.4.2.4.4. **Case 4d:** \( T_R(0) < \bar{C} < T_R(2) \)

When the mean token rotation time falls between the level 2 target rotation time and the level 0 target rotation time, the total utilization of the system can no longer be represented by \( P_2 \). For this case, the level 6 utilization is the fraction of the level 6 peak utilization that is not diminished by level 4 and level 2 traffic. Since network traffic is made up level 2, level 4 and level 6 transmissions, \( P_6(1 - G'_2 - G'_4) \) represents the fraction of level 6 utilization that is not made up of level 2 or level 4 traffic. Therefore,

\[ U_6 = \text{MIN} \left( G'_6, P_6(1 - G'_2 - G'_4) \right) \]

represents the level 6 utilization for this specific circumstance.

Notice that this expression for level 6 utilization is identical to the expression for level 6 utilization derived in section 1.5.4.2.3.4. For that derivation, the mean token rotation time was greater than or equal to \( C_{\sigma} \) and less than the level 2 target rotation time. The same is true for this derivation, except that the mean token rotation time can never equal \( C_{\sigma} \). The fact that \( C_{\sigma} \) was greater than the level 0 target rotation time for the derivation in section 1.5.4.2.3.4, and less than the level 0 target rotation time for this derivation is irrelevant. The derivation is done on the foundation that the mean token
rotation time is less than the level 2 target rotation time, and greater than \( C_r \). The proof from section 1.5.4.2.3.4 is therefore identical for this derivation and is not repeated.

2.5.4.2.4.5. Case 4e: \( \overline{C} = T_R(0) \)

The derivation of the level 6 utilization when the mean token rotation time equals the level 0 target rotation time is very similar to the derivations of level 6 utilization when the mean token rotation time equaled the level 2 and level 4 target rotation times. These derivations were done in sections 1.5.4.2.2.3 and 1.5.4.2.2.1 respectively.

When then mean token rotation time equals the level 0 target rotation time, the mean token rotation time has reached its maximum value. The level 6 utilization, under these circumstances, is dependent upon the level 0 target rotation time. The maximum level 6 utilization will still occur when all \( N \) stations on the control network are transmitting level 6 data for there entire high priority token hold times, but the mean token rotation time will be greater than \( C_r \). Mathematically stated,

\[
H_0 = \frac{[T_s + T_m(6)]N}{T_R(0)}
\]

where \( H_0 \) is the maximum level 6 utilization possible when the mean token rotation is equal to the level 0 target rotation time, and both are greater than \( C_r \).

If the maximum amount of level 6 data has not been transmitted, then the level 6 utilization is equal to the offered load of priority level 6. The level 6 utilization can now be stated as follows,

\[
U_6 = MIN \left( G'_6, H_0 \right)
\]

The proof for this expression of level 6 utilization is identical to the proof for the case of the mean token rotation time equaling the level 4 target rotation time. The only
difference is that the level 0 target rotation time, $T_R(0)$, should be substituted for the level 4 target rotation time, $T_R(4)$, throughout the proof. Note that the same was true when the mean token rotation time equaled the level 2 target rotation time in section 1.5.4.2.4.3.

2.5.4.2.4.6. Case 4f: $C_s \leq \overline{C} < T_R(0)$

When the mean token rotation time falls between the level 0 target rotation time and the level 6 token rotation time, the total utilization of the system can no longer be represented by $P_0$. For this case, the level 6 utilization is the fraction of the level 6 peak utilization that is not diminished by level 4, level 2, and level 0 traffic. Since network traffic is made up all priority levels, $P_6(1 - G'_0 - G'_2 - G'_4)$ represents the fraction of level 6 utilization that is not made up of level 0, level 2, or level 4 traffic. Therefore,

$$U_6 = MIN \left( G'_6, P_6(1 - G'_0 - G'_2 - G'_4) \right)$$

represents the level 6 utilization for this specific circumstance.

The proof for this expression of level 6 utilization is identical to the proof in section 2.5.4.2.2.2. The only difference is that the total utilization is equal to the combination of level 0, level 2, level 4, and level 6 utilizations instead of just level 4 and level 6. The reason being that the mean token rotation time falls between the minimum token rotation time, $C_o$, and level 0 target rotation time, instead of the level 4 target rotation time and $C_s$. This means that level 0 and level 2 traffic may be transmitted. Note that since the mean token rotation time is less than the level 0 target rotation time, the level 0, level 2 and level 4 utilizations are just equal to their respective offered loads.
2.5.4.2.4.7. Case 4g: $\bar{C} < C_s$

Whenever the mean token rotation time is less than the level 6 maximum token rotation time, the entire level 6 offered load may be handled. Therefore,

$$U_6 = G'_6$$

2.5.4.2.4.8. Level 6 Utilization Model for Case 4

The entire level 6 utilization model when the level 6 maximum token rotation time is greater than the level 0 target rotation time, and less than the level 2 and level 4 target rotation times, can now be stated completely.

$$\text{if } \bar{C} = T_R(4) \text{ then } U_6 = MIN \left( G'_6, H_4 \right)$$

$$\text{else if } T_R(2) < \bar{C} < T_R(4) \text{ then } U_6 = MIN \left( G'_6, P_6(1 - G'_4) \right)$$

$$\text{else if } \bar{C} = T_R(2) \text{ then } U_6 = MIN \left( G'_6, H_2 \right)$$

$$\text{else if } T_R(0) < \bar{C} < T_R(2) \text{ then } U_6 = MIN \left( G'_6, P_6(1 - G'_2 - G'_4) \right)$$

$$\text{else if } \bar{C} = T_R(0) \text{ then } U_6 = MIN \left( G'_6, H_0 \right)$$

$$\text{else if } C_s \leq \bar{C} < T_R(0) \text{ then } U_6 = MIN \left( G'_6, P_6(1 - G'_0 - G'_2 - G'_4) \right)$$

$$\text{else if } \bar{C} < C_s \text{ then } U_6 = G'_6$$

The seven conditions for level 6 utilization may also be expressed in terms of utilizations, instead of the mean token rotation time and target rotation times. The first three conditional statements were discussed in previous sections. Only the last four are analyzed here.

Stating that the mean token rotation time is greater than the level 0 target rotation time, but less than the level 2 target rotation time, is equivalent to saying that the total network utilization is greater than the level 0 peak utilization, since the peak utilization only occurs when the mean token rotation time equals the level 0 target rotation time.
The total network utilization consists of the level 2 offered load, level 4 offered load, and level 6 utilization. More formally stated,

\[ G_2' + G_4' + \min \left( G_6', P_6(1 - G_2' - G_4') \right) \equiv \left[ T_R(0) < \bar{C} < T_R(2) \right]. \]

When the mean token rotation time is equal to the target rotation time of level 0, the offered load of level 0 must be greater than the utilization of level 0. Also, the total utilization of the system must be equal to \( P_0 \). This is not to say that the entire utilization is made up of level 0 traffic. In fact it is not, it is made up of level 0, level 2, level 4, and level 6 traffic. Therefore, saying that the mean token rotation time equals the level 0 target rotation time is equivalent to saying that the level 0 offered load plus the level 2, level 4 and level 6 utilizations is greater than the peak level 0 utilization. Since the mean token rotation time is less than the level 2 and level 4 target rotation times, the level 2 and level 4 utilizations are equal to their respective offered loads. More formally stated

\[ G_0' + G_2' + G_4' + \min \left( G_6', H_0 \right) \geq P_0 \equiv \left[ \bar{C} = T_R(0) \right]. \]

For the mean token rotation time to be greater than or equal to \( C_s \), and less than the level 0 target rotation time, the offered loads of level 0, level 2, and level 4, combined with the level 6 utilization, must exceed the peak utilization of level 6. Note that all of the offered loads are considered since they all contribute to the total utilization for a mean token rotation time in this range. More formally stated,

\[ G_0' + G_2' + G_4' + \min \left( G_6', P_6(1 - G_0' - G_2' - G_4') \right) \geq P_6 \equiv \left[ C_s \leq \bar{C} < T_R(0) \right]. \]

Lastly, if both of the previous conditions cannot be satisfied, then the mean token rotation time must be less than \( C_s \). The entire model may now be restated as follows.

\[ \text{if} \left[ G_4' + \min \left( G_6', H_4 \right) \geq P_4 \right] \text{ then} \]
\[ U_6 = \text{MIN} \left( G'_6, H_4 \right) \]

\[
\text{else if} \left[ G'_4 + \text{MIN} \left( G'_6, P_6(1 - G'_4) \right) \geq P_2 \right] \text{then} \\
U_6 = \text{MIN} \left( G'_6, P_6(1 - G'_4) \right)
\]

\[
\text{else if} \left[ G'_2 + G'_4 + \text{MIN} \left( G'_6, H_2 \right) \geq P_2 \right] \text{then} \\
U_6 = \text{MIN} \left( G'_6, H_2 \right)
\]

\[
\text{else if} \left[ G'_2 + G'_4 + \text{MIN} \left( G'_6, P_6(1 - G'_2 - G'_4) \right) \geq P_0 \right] \text{then} \\
U_6 = \text{MIN} \left( G'_6, P_6(1 - G'_2 - G'_4) \right)
\]

\[
\text{else if} \left[ G'_0 + G'_2 + G'_4 + \text{MIN} \left( G'_6, H_0 \right) \geq P_0 \right] \text{then} \\
U_6 = \text{MIN} \left( G'_6, H_0 \right)
\]

\[
\text{else if} \left[ G'_0 + G'_2 + G'_4 + \text{MIN} \left( G'_6, P_6(1 - G'_0 - G'_2 - G'_4) \right) \geq P_0 \right] \text{then} \\
U_6 = \text{MIN} \left( G'_6, P_6(1 - G'_0 - G'_2 - G'_4) \right)
\]

\[
\text{else} \\
U_6 = G'_6
\]

### 2.6. Analyzing Medium Access Delays

This section does an analysis on worst case token rotation times for an IEEE 802.4 token bus. Understanding the worst case token rotation time for a particular priority level will aid learning if the real-time requirements of the distributed system are being met. Note that a priority level's worst case token rotation time is only the same as the worst case queuing delay if all of the frames queued within a token rotation may be transmitted upon the next arrival of the token. Obviously, a large offered load from an access class will make this statement false. However, for infrequent alarm messages transmitted at priority level 6, the worst case token rotation time will closely resemble
the worst case queueing delay. Also, standards such as PROWAY specify a worst case access delay to the medium.

Understanding the performance requirements of the real-time application that will be using the network is important. The capacity of the media and the configuration of the timers should be such that high priority data is never queued for more than a single token rotation. This is the only way to insure access to the medium in a real-time fashion. If the priority mechanism is configured poorly for the application, high priority data may miss its real-time deadline because of large queuing delays at the source. This is not only true for the IEEE 802.4 priority mechanism, but of any priority mechanism.

The models developed in the next few sections assume the following,

- error-free operation of the network
- a constant number of stations on the network,
- $C_o < T_R(0) < T_R(2) < T_R(4)$

### 2.6.1. Worst Case Level 6 Access Delay

The worst case access delay for a level 6 access class occurs when the maximum amount of level 6 and level 4 data are transmitted in a single rotation. Note that level 2 and level 0 transmissions do not have an effect on the worst case level 6 access delay because their target rotation times are less than the level 4 target rotation time.

For a level 6 access class waiting for the token, the maximum amount of level 6 data that will be transmitted, before the token arrives, occurs when all of the other nodes on the network transmit for their entire high priority token hold times (plus an overshoot).
Assuming that the maximum amount of level 6 data is transmitted, then what is the maximum allowable level 4 transmission? The maximum level 4 transmission will occur when no data was transmitted from any node on the network for the previous token rotation. The first node to transmit will transmit its level 6 data, and then transmit level 4 data until its level 4 target rotation time expires. The level 4 data must be transmitted from the first node to transmit any data for the new token rotation. If it were not, then every node that transmitted its level 6 data will decrease the amount of time left to transmit level 4 data.

The worst case level 6 access delay, $D_6$, may now be stated as follows,

$$D_6 = [T_R(4) + T_m(4) - (T_s + T_m(6))] + (N-1)(T_s + T_m(6)) + NT_t.$$  

This reduces to

$$D_6 = T_R(4) + T_m(4) + (N-2)(T_s + T_m(6)) + NT_t.$$  

Note that in the unlikely event that the high priority token hold time is greater than the level 4 target rotation time, the first part of this expression may go negative. The expression does not hold for this case. The maximum level 6 access delay would be the maximum level 6 token rotation time, $C_6$, for that case. However, since the timer configuration is extremely rare, it may be ignored.

### 2.6.2. Worst Case Level 4 Access Delay

The analysis for the worst case access delay for a level 4 access class must be broken into two pieces.

1. When the level 6 maximum token rotation time is greater than the level 4 target rotation time.
2. When the level 6 maximum token rotation time is less than the level 4 target rotation time.

When $C_r$ is greater than the level 4 target rotation time, the worst case access delay for a level 4 access class is infinity. This is because the level 6 transmissions will cause every node's level 4 target rotation time to be exceeded before receipt of the token.

When $C_r$ is less than the level 4 target rotation time, time will be left for every token rotation in which level 4 data may be transmitted. If the level 4 offered load is heavy, and the level 4 bandwidth is being completely used, then all $N$ nodes on the network will have an opportunity to transmit their level 4 data every $N+1$ token rotations. The reason for this is that when the level 4 offered load is large for all nodes on the network, only a single node gets to transmit its level 4 data in a single token rotation. The location of the station that gets to transmit level 4 data rotates around the ring until all nodes have done so. The chart below shows this for three stations. The maximum level 4 access delay, $D_4$, may now be stated as follows,

$$D_4 = (N - 1) \left( T_R(4) + T_m(4) \right).$$

The table below shows how the transmission of level 4 data will occur in a round-robin fashion if many stations have high level 4 offered load and are using all of the level 4 target rotation time. The table maps an example for three nodes on the network. Time progresses downward.
<table>
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<th>Relative Time</th>
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<td>$3T_1/0$</td>
<td></td>
<td></td>
</tr>
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<td>$T_1$</td>
<td></td>
<td></td>
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</tr>
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</tr>
<tr>
<td>$T_n(4)+2T_1$</td>
<td>$T_1$</td>
<td></td>
<td></td>
<td>$T_n(4)/0$</td>
</tr>
<tr>
<td>$T_n(4)+3T_1$</td>
<td>$T_1$</td>
<td></td>
<td></td>
<td>$0/T_n(4)-3T_1$</td>
</tr>
<tr>
<td>$2T_n(4)$</td>
<td>$T_n(4)-3T_1$</td>
<td></td>
<td></td>
<td>$T_n(4)/0$</td>
</tr>
<tr>
<td>$2T_n(4)+T_1$</td>
<td>$T_1$</td>
<td></td>
<td></td>
<td>$T_n(4)/0$</td>
</tr>
<tr>
<td>$2T_n(4)+2T_1$</td>
<td>$T_1$</td>
<td></td>
<td></td>
<td>$T_n(4)/0$</td>
</tr>
<tr>
<td>$2T_n(4)+3T_1$</td>
<td>$T_1$</td>
<td></td>
<td></td>
<td>$0/T_n(4)-3T_1$</td>
</tr>
<tr>
<td>$3T_n(4)$</td>
<td>$T_n(4)-3T_1$</td>
<td></td>
<td></td>
<td>$T_n(4)/0$</td>
</tr>
<tr>
<td>$3T_n(4)+T_1$</td>
<td>$T_1$</td>
<td></td>
<td></td>
<td>$T_n(4)/0$</td>
</tr>
</tbody>
</table>

Figure 5 - An example of the round-robin transmissions that occur when many stations have large offered loads for a lower priority level access class. A different node will use all of the available bandwidth for each rotation of the token.
Each entry in the table is of the form $X / Y$, where $X$ is the token rotation time as seen by that node, and $Y$ is the amount of time that node spent transmitting level 4 data. Entries that represent transmissions are shown in bold. For this example, it is assumed that the offered loads of level 0, 2, and 6 are 0. For the first arrival of the token at each node, it is assumed that no transmissions occurred in the previous rotation. Therefore, the token rotation time detected by all three nodes is the minimum $C_o$. After this first token rotation, station 1 begins by transmitting for its entire level 4 target rotation time. This leaves no time for station 2 or station 3 to transmit level 4 data for that token rotation. They will have to wait for future token arrivals.

2.6.3. Worst Case Access Delay for Other Priority Levels

The worst case access delay for priority levels 2 and 0 are infinity. There will never be a token rotation where a level 2 or level 0 transmission will be guaranteed to occur. There may always be level 4 transmissions to raise the mean token rotation time higher than the level 2 or level 0 target rotation times. This is, of course, assuming that the station in question is using the priority level 4 access class and that the level 4 target rotation time is greater than the level 2 and level 0 target rotation times.
3. Proposed Buffer Insertion Priority Mechanism

3.1. Introduction

The goal of this section, and the entire thesis, is to find a suitable priority mechanism for the buffer insertion protocol. The priority mechanism should improve the performance of a buffer insertion ring when used in real-time distributed applications. As the rest of this section will show, the buffer insertion priority mechanism is developed by adopting the attractive features of the IEEE 802.4 token bus priority scheme.

Section 3.2 discusses the buffer insertion protocol, paying special attention to the two common types of insertion schemes, and lists the problems associated with using a buffer insertion ring in a real-time network. Section 3.3 gives a functional description of the new buffer insertion priority mechanism, while noting the similarities to the IEEE 802.4 token bus priority scheme. Lastly, utilization and throughput analysis is done in section 3.4, and medium access and insertion buffer delays are examined in section 3.5.

3.2. Background

A buffer insertion ring consists of a group of stations connected in a ring topology. The media access protocol of a buffer insertion ring does not rely on a token or a slot for dictating transmissions. Instead, any station may transmit a frame, since it buffers any incoming frames that may arrive while the transmission is taking place. To do this, each station is equipped with a transmit buffer and an insertion buffer. The transmit buffer is used to queue frames, generated by the station, until they can be transmitted. The insertion buffer is used to buffer frames that arrive at the station, but are not destined for the station, while a transmission is taking place. Once a frame reaches its destination,
it is placed into that station's receive buffer, and does not go into the insertion buffer. Frames that are queued in insertion buffers are retransmitted by the stations associated with the insertion buffer. Whether a station's next frame to be transmitted comes from its transmit buffer or insertion buffer is decided in one of two ways. These ways are called ring priority and station priority, and are described in the next two sections.

3.2.1. Ring Priority

A buffer insertion ring using ring priority means that stations are only allowed to transmit when their respective insertion buffers are empty. The insertion buffer of a given station has priority over the transmit buffer of that same station. This implies that, as long as the insertion buffer is as large as the maximum size frame, the insertion buffer will never overflow. If a single frame or multiple frames (if the frames are small) arrive at a station during transmission of the transmit buffer, they are guaranteed to be retransmitted when the station completes the transmission from its transmit buffer. All of the data in the insertion buffer will be transmitted until it is completely empty.

3.2.2. Station Priority

A buffer insertion ring using station priority means that stations transmit immediately if no transmission from an insertion buffer is taking place. In other words, as long as the station is not in the middle of transmitting a frame from its insertion buffer, it will transmit frames queued in its transmit buffer. It will continue to do so until its transmit buffer is empty. The transmit buffer of a given station is of higher priority than the insertion buffer of that same station. This implies that the insertion buffer may overflow if the station is generating a large amount of frames.
3.2.3. Advantages

The buffer insertion protocol has many advantages over conventional token passing media access protocols. Two of these, *spatial reuse* and reduced network management overhead, are discussed in the next couple of sections. From these advantages, one may think that it would naturally follow that a buffer insertion ring would lend itself well to real-time distributed applications. This, however, is not true, as section 3.2.4 points out. Keep in mind, though, that an attempt is made to preserve the advantageous features of the buffer insertion protocol as the new priority mechanism is developed. The priority mechanism will succeed if the advantages of the buffer insertion ring are left intact, and the disadvantages are overcome by the new priority mechanism.

3.2.3.1. Spatial Reuse

Spatial reuse is a big advantage of the buffer insertion ring. Each station on a buffer insertion ring decides to transmit based on the status of its own transmit and insertion buffers. Transmission does not depend on any network wide event such as the arrival of a token or a transmission slot. A station decides when to transmit based on its own internal state. This means that whenever data is queued in the insertion or transmit buffer a frame will be transmitted. This is done no matter what any of the other stations in the network are doing. Therefore, it follows that many stations may be transmitting concurrently. Frames are not lost because they are buffered from station to station, retransmitted according to a ring or station priority approach. Each link connecting two stations together could, in fact, be propagating a frame at the same time every other link is propagating a different, unique frame. This will allow the throughput of a buffer insertion ring to exceed the capacity of the medium. This is called *spatial reuse*. 
3.2.3.2. Small Overhead for Medium Access

A second big advantage to the buffer insertion protocol is the lack of overhead needed to maintain media access control. Since a token does not need to be propagated around the ring, bandwidth is saved. Additionally, logic is not needed to detect duplicate tokens, detect lost tokens, and regenerate tokens. This increases the bandwidth and computing power available to the application.

3.2.4. Problems Associated with Real-Time Applications

The disadvantages of the buffer insertion ring far outweigh the advantages listed in the previous section, at least as far as real-time distributed systems are concerned. Two of the biggest disadvantages are starvation and insertion buffer overflow. Both characteristics of buffer insertion rings are detrimental in a real-time distributed network. The goal of the priority mechanism will be to overcome these disadvantages when using a buffer insertion ring in a real-time distributed network.

3.2.4.1. Starvation

A buffer insertion ring using a ring priority mechanism has the potential for starvation to occur at any station. Starvation occurs when a station cannot transmit its own frame onto the medium because of a high arrival rate of frames into its insertion buffer. Since ring priority dictates that frames already on the ring are of higher priority than frames in a station's transmit buffer, the frames in the insertion buffer keep a station from transmitting.

In the worst case, a station will never be allowed to transmit any of its frames. This occurs when the station's insertion buffer never becomes empty. If the arrival of
frames into the insertion buffer is not as high, the medium access delay for the station to transmit one of its own frames may be very high. An attempt to avoid starvation is handled in the new buffer insertion priority mechanism. This is discussed in section 3.3.2.2.2.

3.2.4.2. Insertion Buffer Overflow

Problems also exist when a station priority scheme is used. Here, the amount of time a frame spends in a station's insertion buffer may be very large if that station is generating a large amount of frames for transmission. Worse yet, if the station blocks out the insertion buffer long enough, the insertion buffer may overflow. This would result in a loss of data. The delays and possible loss of data incurred by the station priority scheme make it undesirable for real-time distributed applications. When using station priority, the message transfer time is not deterministic. In other words, the time it takes for a frame to traverse all of the insertion buffers on the way to its destination is not predictable.

3.3. Functional Description

A functional description of the newly proposed priority mechanism for buffer insertion rings is given in this section. This is done by first listing some desirable characteristics of the IEEE 802.4 token bus priority mechanism. This is then followed by a description of the partitioned insertion buffer, and dedicated insertion buffer. The usage of these two buffers is the cornerstone of the priority mechanism.
3.3.1. Priority Levels

The four priority levels available in the IEEE 802.4 priority scheme will also be available in the buffer insertion priority scheme. For simplicity, they will still be called level 6, level 4, level 2, and level 0, with level 6 representing the highest priority and level 0 the lowest. In the IEEE 802.4 priority mechanism, there is a distinct difference between the high priority level (level 6) and the lower priority levels (level 4, 2, and 0). Mainly, the difference is that access to the medium for level 6 transmissions occurs synchronously, while the lower priority levels access the medium asynchronously.

The synchronous, or level 6, priority transmissions are used to guarantee every station on the network an opportunity to transmit high priority data despite the existing overall offered load. Bandwidth is guaranteed to every station for high priority transmissions. This idea should be extended to the buffer insertion priority mechanism. There should at least be a way that station's needing to transmit high priority frames may be guaranteed a maximum media access time.

The properties associated with lower priority asynchronous transmissions should also be extended to the buffer insertion priority scheme. This priority technique allows bandwidth to be shared between frames of varying priority depending on the offered loads of the three priority levels. A large offering of level 4 frames could use all of the available bandwidth, if necessary. However, if the level 4 offered load is not very large, lower priority transmissions that are not time critical may take place.

3.3.2. Access Classes

The idea of access classes is maintained in the new insertion buffer priority mechanism, although in a modified fashion. Each access class still represents one of four
priority levels. However, a difference arises in how control is passed among the four access classes. In the IEEE 802.4 priority mechanism, control was passed between access classes, from highest to lowest, once the token was received. Since there is no concept of a token in a buffer insertion network, this approach will not work. In the new buffer insertion priority mechanism, the high priority access class and the three lower priority access classes may be thought of as two separate strands of execution. This will become more apparent when the algorithm associated with each access class is presented.

3.3.3. High Priority Transmissions

Level 6, or high priority transmissions, use a dedicated insertion buffer to insure a worst case delay in gaining access to the medium. This differs from the IEEE 802.4 priority mechanism. The IEEE 802.4 priority mechanism allows for synchronous allocation of the medium for level 6 transmissions. Level 6 transmissions in the buffer insertion priority mechanism are handled asynchronously, but incorporate a dedicated insertion buffer that is guaranteed never to remain full, avoiding a starvation condition.

High priority transmissions are expedited around the ring. Whenever a station has a high priority frame queued for transmission, and its dedicated insertion buffer has the available space, the frame is transmitted. This is true even if the station is in the middle of a low priority transmission, or forwarding a frame queued in its insertion buffers. Also, a high priority transmission arriving at an intermediate station is immediately forwarded. Again, this is done even if the intermediate station is transmitting a lower priority frame at the time. However, if the station is transmitting a high priority frame, then the station completes the transmission before forwarding occurs.
3.3.3.1. Dedicated Insertion Buffer

To facilitate high priority transmissions, and to avoid starvation, a dedicated insertion buffer is used. This insertion buffer is used for buffering incoming data while transmitting level 6 frames. To insure that this insertion buffer is available when level 6 frames are queued for transmission, a different approach is used for purging the frame from the ring. Normally, the destination station removes an incoming frame from the ring. Instead of the frame being placed in its insertion buffer, the frame is routed to the station's receive buffer. This is the approach that will be followed for lower priority transmissions that are not experiencing starvation. For high priority transmissions, purging the frame from the ring is handled differently. The frame is not to be purged from the ring by the destination station. Instead, the frame is routed to the destination station's insertion buffer, and copied to its receive buffer. This implies that the high priority frame continues downstream until it reaches the station that it originated from. The high priority frame is then purged from the ring.

Before the frame returns to the station that generated it, the dedicated insertion buffer will function as an extension to the partitioned insertion buffer. This means that incoming data will be shifted into the dedicated insertion buffer first, through the partitioned insertion buffer, and then retransmitted onto the medium. Once the frame returns to the station that it originated from, the dedicated insertion buffer is emptied. This can be done because the returning level 6 frame does not have to be buffered in the station's insertion buffer or receive buffer.
The dedicated insertion buffer may be configured so that more than one level 6 frame may be outstanding at any time. A level 6 frame may be transmitted while space is available in the insertion buffer for incoming data.

3.3.3.2. Expedited Propagation

A high priority frame propagates around the ring much quicker than lower priority transmissions that take place outside a starvation condition. All high priority frames begin and end with a unique bit pattern signifying that they should be expedited around the ring. Whatever a station may be doing when an expedited frame is detected, it must immediately forward the frame to the next station on the ring. An expedited frame is not stored in a station's partitioned or dedicated insertion buffer. This implies that expedited frames may be embedded within lower priority transmissions, or other expedited frames. A station receiving a frame, or buffering a frame in its insertion buffer must always be prepared to receive an expedited frame and retransmit it immediately. Bit stuffing must be used to avoid the unique bit pattern, signifying an expedited frame, from appearing in the header or data area of a frame. Also, a small buffer may be needed at each station to temporarily store an expedited frame for retransmission.

3.3.3.3. Algorithm

When a station has level 6 frames queued for transmission, the dedicated insertion buffer is checked to see if there is enough buffer space to transmit. Buffer space may not be available if the station has several outstanding level 6 transmissions. If buffer space in the dedicated insertion buffer is available, the transmission takes place immediately. If buffer space is not available, the station waits for an expedited frame to return so that
transmission can take place. This should be a short time because of the expedited nature of the frames. During this time, lower priority transmissions may take place if space is available in the partitioned insertion buffer. Any low priority transmission will be pre-empted when the dedicated insertion buffer space is freed, and the high priority frame will be transmitted. Once the high priority transmission completes, the remainder of the lower priority frame is transmitted. This is a perfect example of an expedited frame becoming embedded in a lower priority frame.

If several level 6 transmissions are queued, then they may all be transmitted if the dedicated insertion buffer space remains available. Note that there is not a limit on the amount of level 6 data that may be transmitted. This is done on the assumption that level 6 transmissions are reserved for messages of extreme importance and large frequency.

The transmission algorithm for level 6 frames may now be presented in algorithmic form. The steps presented below may be thought of as their own process that is executing concurrently with another process responsible for lower priority transmissions. The wait statements in lines 1 and 2 of the algorithm indicate that the process is waiting for the associated conditions to be satisfied. When these events occur, this algorithm may preempt the process associated with the lower priority access classes. This guarantees that a level 6 frame is transmitted as soon as the dedicated insertion buffer space is available.

1. wait for a level 6 frame to be queued for transmission
2. wait for the dedicated insertion buffer space to become available
3. transmit the level 6 frame at the front of the queue
4. go to 1
3.3.4. Lower Priority Transmissions

Lower priority transmissions use a partitioned insertion buffer to store incoming data during transmission. This insertion buffer is shared among the level 4, 2, and 0 access classes of a station.

3.3.4.1. Partitioned Insertion Buffer

A partitioned insertion buffer is used to allow media access similar to the asynchronous method available in the IEEE 802.4 priority scheme. This means that it is used to buffer incoming data while level 4, 2, or 0 transmissions are occurring. The buffer is partitioned, meaning that only a subsection of the insertion buffer may be used to store incoming frames while a transmission of a certain priority is taking place. Figure 3 shows an example of the partitioned insertion buffer.

Figure 3 - The insertion buffer for a single station in a buffer insertion network. Notice how partitions of the insertion buffer for lower priority transmissions overlap.
This buffer is used for storing incoming frames while lower priority transmissions are occurring. Notice how the partitions of the insertion buffer overlap. Level 4 transmissions may occur while enough space exists in the entire insertion buffer. Level 2 transmissions may occur depending on the amount of space available in a smaller section of the entire buffer. Finally, level 0 transmissions may occur depending on the amount of space available in the smallest section of the insertion buffer. This means that a level 4 transmission could cause the partitioned insertion buffer to fill so that no space is available in the level 2 or level 0 partitions. In the same manner, a level 2 transmission could cause the partitioned insertion buffer to fill so that no space is available in the level 0 partition. This approach is similar to level 4 data on an IEEE 802.4 network using enough bandwidth that level 2 and level 0 transmissions cannot occur until the next token rotation. It is also similar to level 2 data using enough bandwidth so that level 0 transmissions cannot occur until the next token rotation.

3.3.4.2. Starvation Avoidance

The dedicated insertion buffer used for high priority transmission is also used to avoid starvation of level 4 frames. If a level 4 frame is queued for transmission, it must be transmitted in a predetermined time before it is considered starved from the medium. Starvation occurs because the partitioned insertion buffer associated with lower priority transmissions has been full for too long. This is caused by upstream stations generating large amounts of network traffic that must pass through the partitioned insertion buffer. Obviously, for a real-time network, starvation is unallowable. To avoid starvation, the dedicated insertion buffer is used. This dedicated insertion buffer is the same buffer as-
sociated with high priority transmissions. The starved level 4 frame has its priority level increased to level 6, and put on the level 6 transmit queue. This implies that starved level 4 frames are expedited around the ring in the same manner as level 6 transmissions. The starved level 4 frame is indicated by the same unique bit pattern, and is purged from the ring by the station that it was transmitted by. Hopefully, any additional delay incurred because of a full dedicated insertion buffer will be brief. This should be true due to the expedited nature of all frames that use the dedicated insertion buffer, and the long intervals between frames associated with priority level 6.

3.3.4.3. Algorithm

The lower priority access classes execute together as a single thread of execution. Control is passed sequentially between low priority access classes. When a level 4, 2, or 0 access class executes, a check is done to see if any data is queued for transmission. If not, control is passed to the next lower access class, except in the case of access class 0, which passes control back to access class 4. If access class 2 finds that there is not enough buffer space in its partition of the insertion buffer, control is passed back to access class 4. There is no reason to pass control to access class 0, since its partition of the insertion buffer is a subset of the level 2 partition. Similarly, if access class 4 finds no room in its partition of the insertion buffer, there is no reason to pass control to access class 2. A single iteration that allows each access class to execute is referred to as a cycle. If frames are queued, the partitioned insertion buffer is checked to see if there is enough buffer space to transmit the frame. If buffer space is not available, then control is passed to the next access class.
Providing buffer space is found, the low priority transmission occurs. If many transmissions are queued, then they may all be transmitted if the insertion buffer space remains available. This may occur until the access class reaches its maximum allowable transmissions for a single cycle. This is done so as not to starve an access class of higher priority if no data is entering the insertion buffer. Control is passed to the next access class when there is no more data left in the queue, the partition of the insertion buffer has become full, or the maximum allowable transmission in a cycle has been reached.

The transmission algorithm for a low priority access class is now presented in another form.

1. if no level 4 frames are queued for transmission then go to 11
2. if the level 4 maximum byte transmission for a single cycle has been reached then go to 11
3. check for enough buffer space in the level 4 partition of the insertion buffer
4. if there is enough buffer space in the partition of the insertion buffer to transmit the frame at the front of the queue then go to 9
5. check the starvation timer of the level 4 frame at the front of the queue
6. if the starvation timer has not expired for the level 4 frame at the front of the queue then go to 3
7. requeue the frame at priority level 6
8. go to 1
9. transmit the level 4 frame at the front of the queue
10. go to 1
11. if no level 2 frames are queued for transmission then go to 17
12. if the level 2 maximum byte transmission for a single cycle has been reached then go to 17
13. check for enough buffer space in the level 2 partition of the insertion buffer
14. if there is not enough buffer space in the level 2 partition of the insertion buffer to transmit the frame at the front of the queue then go to 1
15. transmit the level 2 frame at the front of the queue
16. go to 11
17. if no level 0 frames are queued for transmission then go to 1
18. if the level 0 maximum byte transmission for a single cycle has been reached then go to 1
19. check for enough buffer space in the level 0 partition of the insertion buffer
20. if there is not enough buffer space in the level 0 partition of the insertion buffer to transmit the frame at the front of the queue then go to 1
21. transmit the level 0 frame at the front of the queue
22. go to 17

3.4. Analyzing Medium Access Delays

The worst case medium access delay for the new buffer insertion priority mechanism is now examined. As was the case for the IEEE 802.4 priority mechanism, when the maximum level 6 token rotation time is greater than all of the target rotation times, the worst case delay for the lower priority access classes in the buffer insertion network is not deterministic. Unlike the IEEE 802.4 priority mechanism, the worst case medium access delay in a buffer insertion network for priority level 6 is also non-deterministic.

In the IEEE 802.4 priority mechanism, if the timers are configured so that the maximum level 6 token rotation time exceeds the level 4 target rotation time, then level 4 transmissions can be starved by excessive level 6 transmissions. If the maximum level 6 token rotation time is configured to be less than the level 4 target rotation time, then at least one station in the network will have the opportunity to transmit level 4 data. The worst case medium access delays for IEEE 802.4 level 2 and level 0 access classes is in-
finite. Excessive level 4 transmissions in any station will starve the level 2 and level 0 access classes whatever the number of level 6 frames being produced by the station.

In the new buffer insertion priority mechanism, level 6 data is given the opportunity to transmit while there exists space in the station's dedicated insertion buffer. No limit is placed on the amount of level 6 data transmitted in a single cycle. While there exists available space in the station's dedicated insertion buffer, the station may continue to transmit level 6 frames. This obviously implies that the worst case medium access delay for all of the lower priority levels will be infinite. This also implies that the worst case level 6 medium access delay is infinite, since a station may have to wait for dedicated insertion buffer space to free before transmitting. This space is freed when an outstanding level 6 transmission returns. However, the worst case insertion buffer delay that this frame encounters, while traversing the ring, is infinite, thereby making the worst case high priority medium access delay infinite.

In reality, however, level 6 transmissions in a real-time network would be dedicated to urgent messages that would only be generated in critical situations such as abnormal sensor readings (that could occur in a process control environment). The frequency of these types of messages should be very large. Therefore, the worst case delays described above are misleading, but must still be stated as non-deterministic.

Assuming that level 6 transmissions are infrequent and short in length, the worst case level 6 medium access delay becomes deterministic. The worst case medium access delay occurs when a station's level 6 access class is waiting for a previously transmitted frame to return so that space may be freed in the dedicated insertion buffer. This may be a previously transmitted level 6 frame, or a previously transmitted level 4 frame, if a
starvation condition was detected. In either case, the frame is transmitted around the ring in an expedited fashion as explained earlier. Neglecting the computing overhead to detect the expedited frame and forward it, the worst case medium access delay will be the propagation delay for all of the links that the frame was transmitted across. Assuming the next level 6 frame to be transmitted is of maximum size, the worst case medium access delay for a level 6 frame, under the above assumptions, may be mathematically stated as

\[ D_6 = N \cdot T(L_6), \]

where \( D_6 \) is the worst case medium access delay for a level 6 frame, \( N \) is the number of stations in the buffer insertion ring, and \( T(L_6) \) is the time it takes to transmit the maximum size level 6 frame.

### 3.5. Analyzing Insertion Buffer Delays

A worst case delay that must be examined for the buffer insertion ring, that was not examined for the IEEE 802.4 token bus standard, is the delay associated with a frame reaching its destination once it has been transmitted. Obviously, for a token bus, this time is just the propagation delay associated with the physical medium. For a buffer insertion ring, this delay is much more than that. Since a frame is buffered in every station that it needs to pass through, there always exists the possibility of a delay being incurred. If a frame enters a station that is not transmitting, then the frame passes through that station's insertion buffer with little or no delay. However, if the station is transmitting, then the incoming frame must be buffered, causing a delay. The worst case delay occurs when an incoming frame enters an empty insertion buffer just as the station begins to
transmit. The frame may have to wait for the entire insertion buffer to fill before being forwarded. Worse yet, if the station is transmitting level 6 frames and the dedicated insertion buffer is not filling due to lack of incoming data, frames buffered in the insertion buffers could remain there indefinitely. This is true for lower priority frames and high priority frames, since level 6 transmissions could be buffered in a station's dedicated insertion buffer if it is generating a large amount of level 6 traffic. As before, it should be noted that this should never be the case since level 6 transmissions should not occur at high frequencies, and when they do occur they are of very short length. Nevertheless, the worst case insertion buffer delay for lower priority transmissions must be stated as infinite. The worst case insertion buffer delay for high priority transmission is negligible due to the expedited nature of the transmission.

3.6. Analyzing Utilization and Throughput

Utilization and throughput are difficult phenomena to mathematically model in a buffer insertion network. The main reason for this is the phenomena of spatial reuse that is inherent in buffer insertion rings. The total utilization of the network may easily exceed the capacity of the medium. The absolute maximum that the total utilization may become is 100 percent times the number of devices on the network. This occurs when each station on the ring is transmitting data to the station immediately down ring of it. The insertion buffers associated with each station will not be used during this time. Each station appears to have a point-to-point connection with its destination.

The phenomenon of spatial reuse makes it difficult to predict the total utilization of a buffer insertion ring, except for the rare case stated above. Consequently, the mathe-
Mathematical observations made for the new buffer insertion priority mechanism examine each station individually to model a particular station's contribution to the total utilization of the network. The total utilization is dependent upon the destinations of each station's transmissions. A simplifying assumption may be made that all stations transmit uniformly to all others, but this will not model the actual utilization of a real world buffer insertion network more closely than the individual models that will be presented. To obtain a solid understanding of how the new buffer insertion priority mechanism performs, simulations should be performed. This is the next logical step to this thesis.

The utilization analysis done for the IEEE 802.4 priority mechanism was based upon the mean token rotation time of the ring. A similar quantity is used to model the utilization in the buffer insertion ring when using the new priority mechanism. This quantity is the mean number of bits in the insertion buffer. The mean number of bits in a station's insertion buffer makes up how much bandwidth the station has available for transmitting frames of various priority levels.

3.6.1. **High Priority Transmissions**

The analysis for level 6 utilization is based upon the mean number of bits used in a station's dedicated insertion buffer. This is unlike the utilization analysis done for the low priority levels in the next section, which is mainly based upon the partitioned insertion buffer. Note that the dedicated insertion buffer is only used for level 6 transmissions and level 4 starvation avoidance. Whenever either frame is transmitted it is not purged from the ring until it returns to the originating station. This guarantees a maximum medium access delay time before a full dedicated insertion buffer has room available for
transmission. Throughout this section, references to level 6 frames also hold for level 4 frames undergoing starvation.

The level 6 utilization will equal its offered load while the dedicated insertion buffer does not become full. This may be an indefinite amount of time if the station in question does not have any frames arriving that need to pass through its insertion buffers. Again, the level 6 utilization for a single station cannot surpass the capacity of the medium. Therefore, if the offered load of level 6 frames, at a particular station, exceeds the capacity of the medium, and the dedicated insertion buffer remains unfilled, then the level 6 utilization, for that station, peaks at 100 percent. Mathematically stated,

\[
\text{if } K_d(i) < M_6 \text{ then } U_6(i) = \min \left( G'_6(i), \ 1.0 \right),
\]

where \( i \) is the identification of the station, \( K_d \) is the mean number of bits in the dedicated insertion buffer, and \( M_6 \) is the maximum number of bits that the dedicated insertion buffer may hold (in other words, the size of the dedicated insertion buffer).

When the mean number of bits used in the dedicated insertion buffer reaches the capacity of the buffer, the level 6 utilization does not drop to zero. Instead, it becomes dependent on the time it takes for outstanding level 6 transmissions to return to the station so dedicated insertion buffer space may be freed. This time is kept short, due to the expedited nature of level 6 transmissions. The maximum delay for this to occur was already modeled in section 3.5. The level 6 utilization model may now be stated as

\[
U_6(i) = \begin{cases} 
G'_6(i), & \text{if } K_d(i) < M_6 \\
\frac{T(L_6)}{T(L_6) + D_6}, & \text{if } K_d(i) = M_6
\end{cases}
\]

where \( M_6 \) is the size of the dedicated insertion buffer, \( L_6 \) is the maximum level 6 message

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size, $D_6$ is the maximum delay in freeing $L_6$ bits in the dedicated insertion buffer (which is equivalent to saying that it is the worst case medium access delay for a level 6 access class), $T(L_6)$ is the time it takes to transmit $L_6$ bits, and $K_d$ is the mean number of bits in the dedicated insertion buffer.

### 3.6.2. Lower Priority Levels

The utilization of lower priority levels in a buffer insertion ring is very similar to the utilizations expressed for an IEEE 802.4 network. The buffer insertion utilization model is based on the following values:

- the mean number of bits used in a station's partitioned insertion buffer,
- the station's offered load for a particular priority level.

If the mean number of bits used in station $i$'s partitioned insertion buffer, $K_p$, is less than that access level's partition size by at least one message size, then it is safe to say that station $i$ can transmit its offered load for that access class. This statement may be made despite the priority level being 4, 2, or 0. It is, however, more likely to be the case for priority level 4 than it is for priority levels 2 or 0, because the level 4 partition is larger than the level 2 or 0 partitions. Similarly, it is more likely to be the case for priority level 2 then it is for priority level 0, because the level 2 partition size is also larger than the level 0 partition size.

If station $i$ is not receiving data into its insertion buffer, while transmitting, then the entire offered load is being handled. This is true until the offered load exceeds the capacity of the medium. It is possible that this will occur and the partition of the insertion buffer associated with the priority level will still have space available. In this case, the transmit queue associated with the station begins to fill.
The utilization of a station when the mean number of bits in the insertion buffer is less than the partition size for a particular access class may now be stated as

\[ U_j(i) = \text{MIN} \left( G'_j(i), \ 1.0 \right) \quad \text{where} \ j = 0, 2, \ or \ 4 \ and \ i = 0...N \]

where \( j \) is the priority level and \( i \) identifies the station.

It should be noted that this expression for utilization holds true even if a very small section of the partition in the insertion buffer is free. As long as data is not arriving while transmission is taking place, the offered load can be handled up to the capacity of the medium. Once the mean number of bits in the insertion buffer equals or exceeds the partition for a particular access class, the utilization for that priority level drops to zero (if a starvation detection mechanism is not in place). Therefore, if the issue of starvation is ignored for the moment, the utilization for a single node, \( i \), may now be modeled as follows;

\[
U_j(i) = \begin{cases} 
\text{MIN} \left( G'_j(i), \ 1.0 \right), & \text{if} \ K_p(i) < M_j \\
0, & \text{if} \ K_p(i) \geq M_j 
\end{cases}
\]

where \( K(i) \) is the mean number of bits in the insertion buffer at station \( i \), and \( M_j \) is the size of the insertion buffers partition for access class \( j \). This equation holds for any low priority access class.

When starvation avoidance is added to the new buffer insertion priority mechanism, the utilization model for priority level 4 changes. It differs from the level 2 and level 0 utilization models because the starvation avoidance algorithm being employed only accounts for level 4 and level 6 access classes. The algorithm could be extended to all access classes, but in a real-time control network the lower two access classes are
probably being used for things such as non-critical displays and file transfers. These types of transmissions are not as time-critical and should be sacrificed in a busy network so that real-time data may meet their delivery deadlines. Since starved level 4 frames actually have their priority levels increased to level 6, are put in the level 6 transmit queue, and are transmitted by the level 6 access class in the same fashion as high priority frames, the analysis done for level 6 utilization in the previous section is also true for level 4 utilization, when the level 4 partition in the partitioned insertion buffer is full.

The model for level 4 utilization with starvation avoidance may now be stated as

\[
U_4(i) = \begin{cases} 
  \text{MIN} \left( G'_4(i), \ 1.0 \right) & \text{if } K_P(i) < M_4 \\
  \alpha U_6(i) & \text{if } K_P(i) \geq M_4
\end{cases}
\]

where \( \alpha \) is the fraction of the level 6 utilization that is made up of level 4 frames that have undergone starvation. Similarly, the level 6 utilization related strictly to level 6 generated frames and not to level 4 frames in a starvation condition may be stated as

\[
U'_6(i) = (1 - \alpha) U_6(i).
\]

Note that the worst case medium access delay for a level 6 frame (or a starved level 4 frame) is comparable to that of a token ring or token bus. If the dedicated insertion buffer is full, the level 6 access class must wait for previously transmitted frames to return. This is similar to the way stations in a token passing protocol must await the return of the token. The frames that the buffer insertion access classes are awaiting, take long to return if intermediate stations also need to transmit high priority frames. This is similar to the mean token rotation time increasing as the number of transmissions from each station in a single token rotation increases. In fact, under normal operating conditions, when the
number of level 6 transmissions is small and infrequent, the buffer insertion ring will perform better than a token passing ring because of the expedited nature of level 6 transmissions.
4. Conclusion

The final section of this thesis makes some observations on the success of the new buffer insertion priority mechanism. It also discusses the performance of the new buffer insertion priority scheme with respect to the standardized IEEE 802.4 priority scheme. Lastly, some reasons why it is difficult to apply real-time priority transmissions to a buffer insertion ring are examined.

The new buffer insertion priority mechanism is based on observations of the IEEE 802.4 priority mechanism. Differences do exist, however, in the behavior of the two protocols. This does not imply that the new buffer insertion priority mechanism has failed. The goal of this thesis was to apply knowledge gained from studying a well-documented priority mechanism, and to apply that knowledge to enhance the capabilities of the buffer insertion ring in real-time distributed applications. The new buffer insertion protocol should be judged on its ability to perform well in a real-time environment, not on how utilization and delay characteristics of each compare. If the mathematical observations of the new buffer insertion priority mechanism would have matched those of the IEEE 802.4 priority mechanism, then there would be no doubt as to the success of the new priority scheme. There are, however, varying degrees of success, and other correct answers than those presented by the characteristics of the IEEE 802.4 priority mechanism.

The performance of the buffer insertion ring for real-time distributed applications has been improved. There is no doubt that the new priority mechanism improves the performance of a buffer insertion network under real-time constraints. It is not, however, up to par with the performance of the IEEE 802.4 priority mechanism, when considered un-
der heavy loads. The properties associated with spatial reuse may never allow for a real-
time buffer insertion network to appear as capable as an IEEE 802.4 token bus on paper.
The fact that the worst case insertion buffer delay for all levels of priority is non-
deterministic is a downfall of the new buffer insertion mechanism. However, this ob-
servation should not be made without saying that the insertion buffer delays only grow to
infinity when many level 6 frames are being generated. The degree of insertion buffer
delay is directly related to the amount of high priority level 6 frames circulating the ring.
Reserving priority level 6 for very important transmissions implies that this will be infre-
quent. For example, in a process control environment, level 6 transmissions would be
reserved for alarm messages. These would only be generated in case of a plant failure,
and their size would be very small. It is safe to say that even under the most severe plant
failures, level 6 transmissions would still not cripple transmissions on the buffer insertion
ring. When these observations are considered with other assets of the buffer insertion
ring such as spatial reuse, and minimum network overhead, trade-offs become apparent.
The buffer insertion ring with the new priority mechanism presented here may not be
suitable for real-time systems with hard deadlines. It is, however, suited for most real-
time distributed applications.

If the performance of the new buffer insertion priority mechanism were to be
compared to the IEEE 802.4 priority scheme, it would most closely resemble the IEEE
802.4 timer configuration in which the maximum level 6 token rotation time, $C_n$, is con-
figured to be greater than all of the target rotation times. When this is the case, a large
amount of level 6 transmissions will cause the medium access delay for the lower priority
access classes to grow towards infinity. The medium access delays grow large because the level 6 transmissions allow every station's target rotation timers to expire. This may be directly compared to the performance of the new buffer insertion priority scheme. A large amount of level 6 transmissions in a buffer insertion network will also drive the medium access delay towards infinity. This occurs because of the expedited nature of level 6 transmissions blocking out other transmissions. Unlike the IEEE 802.4 priority mechanism, the transmission delay, or insertion buffer delay, also grows toward infinity because of a large number of level 6 transmissions. Any lower priority frames that are caught in an intermediate station's insertion buffer, dedicated or partitioned, will remain there as long as level 6 frames are being transmitted from that station, or are being expedited through that station. In either case, if the station or stations generating the level 6 traffic are not buffering incoming data, the level 6 transmissions could continue forever (however improbable this may be). An IEEE 802.4 token bus network experiences no transmission delays because of the bus topology. All frames reach all station's connected to the bus at approximately the same time, neglecting some time for medium propagation delays.

The new buffer insertion mechanism is not similar to the three other cases associated with the analysis of the IEEE 802.4 priority scheme. When the maximum level 6 token rotation time, \( C_p \), is less than the greatest target rotation time, lower priority transmissions may still occur. This is not the case concerning the new buffer insertion priority scheme. The new priority mechanism places no bounds on the number of level 6 frames that may be transmitted at any given time, possibly allowing lower priority trans-
missions to intervene if space were available in the partitioned insertion buffer. Limiting the number of level 6 transmissions, in some manner other than the dedicated insertion buffer becoming full, could be made a configurable option in the new buffer insertion priority mechanism. This option would only be used for any rare distributed applications that may generate a high load of level 6 traffic.

The utilization models developed for the new buffer insertion priority mechanism are not as complete as those representing utilization for the IEEE 802.4 priority scheme. They cannot be. It is difficult to model the utilization of an entire buffer insertion network because of spatial reuse. The buffer insertion network does not behave as a token passing system where stations using the medium transmit sequentially. Each transmission may or may not affect other concurrent transmissions depending on the destination station.

The assumption was made that the offered load at each priority level was evenly distributed about the ring, and that the destinations of all frames of a certain priority level being generated from a single station were evenly distributed. This implied that the mean number of bits in the partitioned and dedicated insertion buffers were the same in all stations. These assumptions produced a suitable model to study the characteristics of the new buffer insertion protocol, but the assumptions leave little probability of imitating real world scenarios. To more fully understand the new buffer insertion protocol presented in this thesis, simulations should be done. A direct comparison to the presented model can then be made, and more realistic operating conditions may be tested.
In summary, the new buffer insertion priority mechanism has been mathematically shown to improve the performance of a buffer insertion network for real-time distributed applications. Although the new priority mechanism may not be suitable for certain hard real-time systems, its performance characteristics are satisfactory for a wide range of real-time distributed applications.
5. Glossary

\( \alpha \) - ratio of data bits to total bits transferred

\( C_c \) - minimum token rotation time

\( C_s \) - maximum level 6 token rotation time

\( \bar{C} \) - mean token rotation time

CSMA - carrier sense multiple access

\( D_i \) - worst case media access delay for access class \( i \)

DA - destination address

ED - end delimiter

FC - frame control

FCS - frame check sequence

FDDI - Fiber Distributed Data Interface

\( G \) - offered load without overhead bits

\( G' \) - offered load with overhead bits

\( H_i \) - maximum level 6 utilization when the level 6 maximum token rotation is less than the target rotation for access class \( i \)

IEEE - Institute of Electrical and Electronics Engineers

\( K_d(i) \) - mean number of bytes in dedicated insertion buffer of station \( i \)

\( K_p(i) \) - mean number of bytes in partitioned insertion buffer of station \( i \)

\( M \) - maximum size of insertion buffer

\( N \) - number of station in the network

\( P \) - peak utilization

PROM - Programmable Read Only Memory
$S$ - throughput

$SA$ - source address

$SD$ - start delimiter

$T_m(i)$ - maximum overshoot for access class $i$

$T_R(i)$ - target rotation time of access class $i$

$T_t$ - token passing time between adjacent stations

$U$ - utilization
6. References


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