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by

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Abstract

The IEEE 1394 is a standard for the high performance serial bus interface. This standard has the isochronous transfer mode that is suitable for real-time applications and the asynchronous transfer mode for delay-insensitive applications. It can be used to construct a small-size local area network. We have modeled this standard by a simple queueing model under some assumptions and calculated the average waiting time of a packet in the buffer in the steady state. We also give some numerical results in order to estimate the performance of this serial bus roughly.

1 Introduction

The IEEE 1394 is a high performance serial bus interface as a specification of the bus by which computers and I/O equipments are interconnected together [1] [2] [3]. It was standardized by IEEE in 1995 on the basis of the specification of the bus called *Fire Wire* that had been developed by Apple, Inc.

The IEEE 1394 can be used not only as a bridge bus but also as an interconnection among personal computers, peripheral devices, video decks, digital video cameras, and so on. This ability enables us to construct a small-size local area network environment such as Small Office Home Office (SOHO). For example, the IEEE 1394 is considered to construct a home network in [4]. When it was standardized in 1995, the maximum transmission speed of the bus was 400Mbps. Then IEEE planned to specify a version of higher speed called *P1394b* by the summer of 1999. It will enhance the current IEEE 1394 to be used to construct a large-size local area network in the office and other sites.

The IEEE 1394 has several characteristics that are different from any other LANs such as the Ethernet, the token-ring, etc. We put special emphasis on the following two characteristics related to the performance of this bus.

One is that the IEEE 1394 uses an *arbitration method* for the multiple access control. This method is of centralized type and there exists a special node that controls the access to the bus in the network.

The other is that the IEEE 1394 has two kinds of data transfer modes called *isochronous transfer mode* (ITM) and *asynchronous transfer mode* (ATM). In the ITM, the IEEE 1394 guarantees almost exactly periodic data transmissions. Therefore, the ITM is suitable for real-time applications. In the ATM, a node attached to the bus can send only one packet at a time when the bus is free. Besides, the node that wants to transmit a packet in the ATM must defer to other nodes transmitting packets in the ITM. It means that the transmission of a packet in the ITM has a higher priority than that in the ATM. In the IEEE 1394, time is divided into fixed-size frames called *cycles.* The duration of a cycle is 125 μseconds. At most 80% of this time is available to transmit packets in the ITM. The rest of this time is available for the packets in the ATM. During this time, the node that wants to transmit a packet in the ITM must defer to the nodes transmitting packets in the ATM. The capacity of transmitting packets in the ITM per cycle is independent of the traffic load in the ATM, while the that of transmitting packets in the ATM per cycle depends on the traffic load in the ITM. Because of this asymmetry, the performance of the bus in the ATM is affected by the behavior of the traffic in the ITM.

The purpose of this paper is to study the performance of the bus in terms of the average waiting time of an arbitrary packet in the buffer in the steady state. We first consider the number of isochronous packets in the buffer, then that of asynchronous packets. Given some assumptions, we derive the probability generating function for the number of the asynchronous packets in the buffer by a Markov chain under certain overhead of the isochronous traffic. We finally calculate the average waiting time of an asynchronous packet in the buffer as a performance index of the bus.

2 Multiple Access Control and Data Transfer Modes

In this section, we describe the multiple access control and the data transfer modes in the IEEE 1394. See Figure 1.

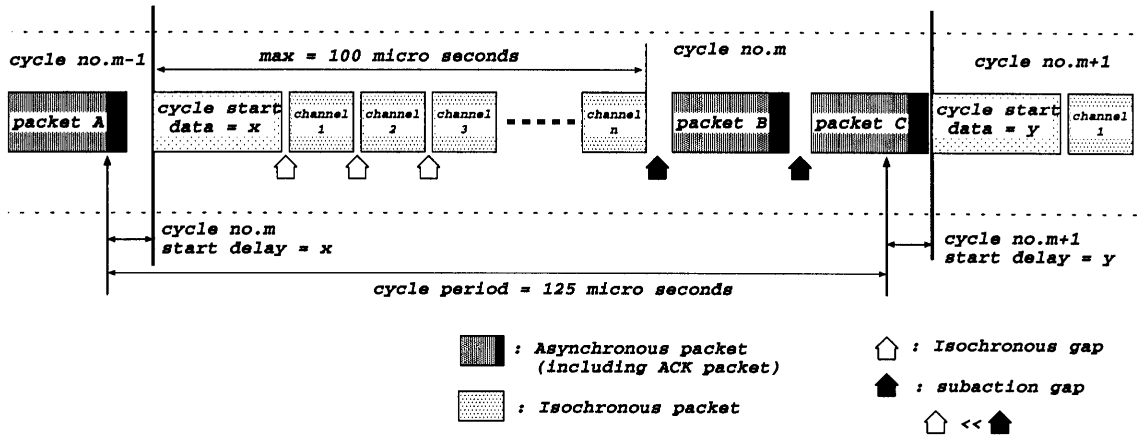

Figure 1: The organization of a cycle in the IEEE 1394 [1].

Since the IEEE 1394 is a bus specification, more than one node cannot transmit data simultaneously. Therefore, the IEEE 1394 needs some multiple access control as the Ethernet does. It uses an access method called *arbitration.* There are two types of arbitration, namely, *isochronous arbitration* and *asynchronous arbitration.*

2.1 Isochronous Transfer Mode

The transmission of a packet in the ITM is divided into three phases:

1. Isochronous arbitration (arb phase)

2. Data transfer (data phase)

3. Isochronous gap (gap phase)

According to [5, p.117], the isochronous arbitration is done as follows.

a. All nodes attached to the bus set their clock by a *cycle start* (CS) *packet* sent by the *root.* The root is a node that controls and manages access to the bus. The root sends a CS packet every 125 μseconds. The interval between consecutive CS packets is a cycle. An overall network cycle synchronization must be maintained.

b. A node that wishes to transmit a packet sends the root a request for the transmission after it detects an *isochronous gap* (IG). The IG is a state in which no signal propagates on the bus during for a short time.

c. The root assigns a certain channel to the node that has first sent a request, and this node transmits a packet. After that, this node is prohibited from transmitting until the next cycle. Since at most 100 μseconds are available to transmit packets in the ITM within a cycle, the transmission request is refused when the time taken for transmitting packets in the ITM exceeds 100 μseconds.

d. Steps 1, 2 and 3 are repeated. In the case of the ITM, no ACK is returned. The node assigned a channel by the root can transmit one packet per cycle unless it sends the root a signal to release the channel.

2.2 Asynchronous Transfer Mode

The transmission of a packet in the ATM is divided into four phases:

1. Asynchronous arbitration (arb phase)

2. Data transfer (data phase)

3. Acknowledgment (ack phase)

4. Subaction gap or arbitration reset gap (gap phase)

According to [5, p.116], the process of the asynchronous arbitration is as follows.

a. A node that wishes to transmit a packet sends a request for transmission to the root after it detects a *subaction gap* (SG) or an *arbitration reset gap* (ARG). The SG is a state in which no signal propagates on the bus for a short time. The ARG is a state in which no signal propagates on the bus for a period that is much longer than an IG.

b. The root allows the node that has first sent a request to transmit a packet. Then, this node transmits only one packet. After that, it is prohibited from transmitting until it detects an ARG.

c. The node that receives a packet returns an ACK. Then the bus gets in the state in which no signal propagates.

d. Steps 1, 2 and 3 are repeated until all nodes complete transmitting their packets. After that, an ARG occurs, and every node can again send the root a request for the transmission.

The mechanism by which the transmission of a packet in the ITM has priority over that in the ATM works as follows. Assume that there are two nodes. One of them wishes to transmit a packet in the ITM, and the other wishes to transmit a packet in the ATM. At the beginning of a cycle, the root sends a CS packet. After that, the bus enters a state in which no signal propagates on the bus. After some time, both nodes identify this state as an IG since it is shorter than the SG and the ARG. Thus the node that has a packet in the ITM transmits first.

3 Analytical Model

A discrete-time queueing system is considered as a model of the IEEE 1394. First, some assumptions are made in order to make the analysis tractable. Then we construct a Markov chain for the number of packets in the buffer.

3.1 Modeling Assumptions

Our modeling assumptions are as follows.

- **Discrete time:** Time is divided into fixed-length intervals, called *slots*, such that the transmitter can transmit exactly one packet during a slot both in the ITM and in the ATM. It implies that the arbitration, data transfer, and the IG occur in one slot in the ITM and that the arbitration, data transfer and the SG or ARG occur in one slot in the ATM.

- **Maximum number of packets transmitted in a cycle:** The maximum number of isochronous packets transmitted within a cycle is M, and that of both isochronous and asynchronous packets is N. This means that a cycle is divided into N slots, and that it may take up to M slots to transmit isochronous packets and up to $[N - M]^+$ slots to transmit asynchronous packets in the cycle.

- **Multiple Access Control:** The arbitration method explained in Section 2 is not taken into consideration in our model.

- **Simple Queueing Model:** There is an infinite-capacity FIFO queue for each transfer mode. All isochronous packets generated in the nodes flow into its queue, so do all asynchronous packets.

- **Arrival Streams:** The arrival streams of isochronous and asynchronous packets from all nodes are considered to be Poisson with rates λ_A and λ_I, respectively.

- **Packet Transmission:** No packet arriving in a cycle is transmitted in the same cycle. It is transmitted only after the next cycle. Thus the packets transmitted in nth cycle are those that arrived at the queue before the nth cycle. In the real system, however, a packet arriving in a cycle can be transmitted immediately if the bus is free.

3.2 Markov Chain Model

A discrete-time Markov chain is used as a means of modeling isochronous and asynchronous traffic. The average waiting times of isochronous and asynchronous packets in the steady state are obtained using this model in Section 4.

Let X_n be the number of isochronous packets in the queue at the beginning of the nth cycle, and let Y_n be the number of asynchronous packets in the queue at the beginning of the nth cycle. Let λ_I(/slot) be the arrival rate of isochronous packets, that is, λ_I is the average number of packets that arrive in a slot. Similarly, let λ_A(/slot) be the arrival rate of asynchronous packets, that is, λ_A is the average number of packets that arrive in a slot. Some additional random variables are introduced. Let X_n^h be the number of isochronous packets in the queue at the beginning of the $h+1$ th slot in the nth cycle. Let Y_n^h be the number of asynchronous packets in the queue at the beginning of the $h+1$ th slot in the n th cycle. Finally, let $Po(\lambda)$ be a random variable whose distribution is Poisson with rate λ.

The relationships between these random variables are given as follows.

$$\begin{aligned}
X_{n+1} &= Po(N\lambda_I) + [X_n - M]^+ && && \text{(1a)}\\
Y_{n+1} &= Po(N\lambda_A) + [Y_n - (N - \min(M, X_n))]^+ && && \text{(1b)}\\
X_n^h &= Po(h\lambda_I) + [X_n - \min(h, M)]^+ && h = 1, \ldots, N-1 && \text{(1c)}\\
Y_n^h &= \begin{cases} Po(h\lambda_A) + [Y_n - (h - \min(h, X_n))]^+ & h = 1, \ldots, M \\ Po(h\lambda_A) + [Y_n - (h - \min(M, X_n))]^+ & h = M+1, \ldots, N-1 \end{cases} && && \text{(1d)}
\end{aligned}$$

In (1a), X_{n+1} consists of two parts. One is the number of isochronous packets arriving during the nth cycle, which is $Po(N\lambda_I)$. The other is the number of isochronous packets remaining in the queue after the ITM transmission phase in the nth cycle, which is $[X_n - M]^+$. In (1b), Y_{n+1} also consists of two parts. One is the number of asynchronous packets arriving during the nth cycle, which is $Po(N\lambda_A)$. The other is the number of asynchronous packets remaining in the queue after the ATM transmission phase in the nth cycle, which is $[Y_n - (N - \min(X_n, M))]^+$. In (1c), X_n^h consists of two parts. One is the number of isochronous packets arriving during h slots, which is $Po(h\lambda_I)$. The other is the number of isochronous packets remaining in the queue at the end of the hth slot in the nth cycle, which is $[X_n - \min(h, M)]^+$. In (1d), Y_n^h also consists of two parts. One is the number of asynchronous packets arriving during h slots, which is $Po(h\lambda_A)$. The other is the number of asynchronous packets remaining in the queue at the end of the hth slot in the nth cycle, which is $[Y_n - (h - \min(h, X_n))]^+$ if $h = 1, \ldots, M$, or $[Y_n - (h - \min(M, X_n))]^+$ if $h = M+1, \ldots, N-1$. For simplicity, if we define

$$\begin{aligned}
X_{n,h} &:= [X_n - \min(h, M)]^+ && h = 1, \ldots, N-1 && \text{(2a)}\\
Y_{n,h} &:= \begin{cases} [Y_n - (h - \min(h, X_n))]^+ & h = 1, \ldots, M \\ [Y_n - (h - \min(M, X_n))]^+ & h = M+1, \ldots, N \end{cases} && && \text{(2b)}
\end{aligned}$$

we can write (1a)–(1d) as

$$\begin{aligned}
X_{n+1} &= Po(N\lambda_I) + X_{n,N} && && \text{(3a)}\\
Y_{n+1} &= Po(N\lambda_A) + Y_{n,N} && && \text{(3b)}\\
X_{n+1}^h &= Po(h\lambda_I) + X_{n+1,h} && h = 1, \ldots, N-1 && \text{(3c)}\\
Y_{n+1}^h &= Po(h\lambda_A) + Y_{n+1,h} && h = 1, \ldots, N-1 && \text{(3d)}
\end{aligned}$$

Note that $Y_{n,h}$, and therefore Y_n, depend on X_n. Thus the isochronous traffic is independent of the asynchronous traffic while the asynchronous traffic depends on the isochronous traffic.

According to the specification of the IEEE 1394, it may take up to 80% of a cycle time to transmit isochronous packets. For example, if $N = 10$, then $M = 8$. The relationship among X_n, X_n^h, Y_n and Y_n^h in this case is illustrated in Figure 2.

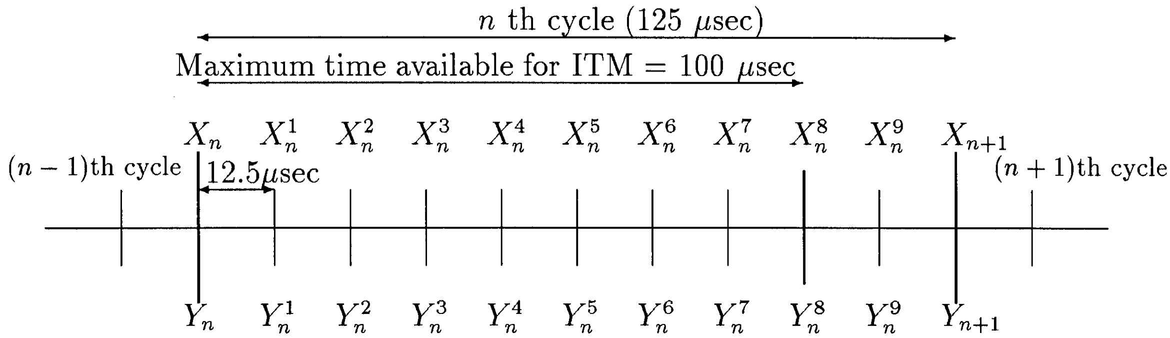

Figure 2: Relationship among X_n, X_n^h, Y_n and Y_n^h.

4 Analysis

In this section, we obtain the average waiting time of an isochronous and an asynchronous packet as the performance measure. The stability conditions are also derived.

4.1 Isochronous Transfer Mode

We first consider the isochronous traffic, which can be treated independently of the asynchronous traffic.

From (3a) and (3c), the probability generating functions for X_n and X_n^h are given by

$$\begin{aligned} X_n(z) &= e^{N\lambda_I(z-1)} X_{n-1,N}(z) \\ X_n^h(z) &= e^{h\lambda_I(z-1)} X_{n,h}(z) \qquad h = 1, \ldots, N \end{aligned} \tag{4}$$

According to the probabilities

$$\begin{aligned} P([X_n - h]^+ = 0) &= P(X_n \le h) \\ P([X_n - h]^+ = k) &= P(X_n = k + h) \qquad k = 1, \ldots \end{aligned}$$

the probability generating function of $X_{n,h}$ is given by

$$X_{n,h}(z) = \begin{cases} \dfrac{1}{z^h}\left[X_n(z) + \sum\limits_{k=0}^{h-1} P(X_n = k)(z^h - z^k)\right] & h = 1, \ldots, M \\ \dfrac{1}{z^M}\left[X_n(z) + \sum\limits_{k=0}^{M-1} P(X_n = k)(z^M - z^k)\right] & h = M+1, \ldots, N \end{cases} \tag{5}$$

Let $X(z)$ be the probability generating function for the number of isochronous packets in the queue at the beginning of a cycle in the steady state. Also let $X^h(z), h = 1, 2, \ldots, N-1$, be the probability generating function for the number of isochronous packets in the queue at the beginning of the $h+1$ th slot of a cycle in the steady state. In addition, $\pi_k^x, k = 0, \ldots, M-1$, is defined as the probability that the number of isochronous packets in the queue is k at the beginning of a cycle in the steady state. We then get $X(z)$ and $X^h(z)$ as follows.

$$X(z) = \frac{e^{N\lambda_I(z-1)}(\sum_{k=0}^{M-1}(z^M - z^k)\pi_k^x)}{z^M - e^{N\lambda_I(z-1)}} \tag{6}$$

$$X^h(z) = \begin{cases} \dfrac{e^{h\lambda_I(z-1)}(X(z) + \sum_{k=0}^{h-1}(z^h - z^k)\pi_k^x)}{z^h} & h = 1, \ldots, M \\ \dfrac{e^{h\lambda_I(z-1)}(X(z) + \sum_{k=0}^{M-1}(z^M - z^k)\pi_k^x)}{z^M} & h = M+1, \ldots, N-1 \end{cases} \tag{7}$$

The number of roots of a denominator of $X(z)$ can be found by applying Rouché 's theorem.

Rouché 's theorem [6, p.20]: If $f(z)$ and $g(z)$ are analytic functions of z inside and on a closed contour C on the complex z-plane, and if also $|g(z)| < |f(z)|$ on C, then $f(z)$ and $f(z) + g(z)$ have the same number of zeros inside C.

In the present case, $f(z)$ and $g(z)$ are defined by

$$f(z) = z^M \tag{8}$$

$$g(z) = -e^{N\lambda_I(z-1)} \tag{9}$$

On a circle $|z| = 1 + \epsilon$ for a small $\epsilon > 0$, we have

$$|g(z)| \leq 1 + \epsilon N\lambda_I + o(\epsilon) \tag{10}$$

$$|f(z)| = (1+\epsilon)^M = 1 + M\epsilon + o(\epsilon) \tag{11}$$

Therefore, $|g(z)| < |f(z)|$ if

$$\lambda_I < \frac{M}{N} \tag{12}$$

which is the stability condition for the isochronous traffic.

If the last inequality holds, the number of roots of a denominator of $X(z)$ is equal to that of $f(z)$, which is M. Let such roots but 1 be $z_1, \ldots, z_{M-1}$. If $z_k, k = 1, \ldots, M-1$, is substituted into $X(z)$, then the numerator of $X(z)$ must be 0. These $M-1$ roots are calculated by Lagrange's theorem.

Lagrange's theorem [6, p.20]: Let $f(z)$ and $g(z)$ be analytic on and inside a closed contour C surrounding a point a, and let ω be such that the inequality

$$|\omega g(z)| < |z - a| \tag{13}$$

is satisfied at all points z on C. Then the equation

$$z = a + \omega g(z) \tag{14}$$

in z has exactly one root inside C, and further, any function $f(z)$ which is analytic on and inside C can be expanded as a power series in ω by the formula

$$f(z) = f(a) + \sum_{n=1}^{\infty} \frac{\omega^n}{n!} \frac{d^{n-1}}{dz^{n-1}} \left(\frac{df(z)}{dz} \cdot g(z)^n \right) \Bigg|_{z=a} \tag{15}$$

In our case, we set values or functions to a, ω, $g(z)$, and $f(z)$ as follows.

$$a = 0, \qquad \omega = e^{2\pi mi/M} \quad m = 1, \ldots, M-1$$

$$g(z) = (e^{N\lambda_I(z-1)})^{1/M}, \qquad f(z) = z \tag{16}$$

where $i := \sqrt{-1}$. Then, the $M-1$ roots of the denominator of $X(z)$ inside the unit circle are given by

$$z_m = \sum_{n=1}^{\infty} \frac{e^{\frac{2\pi mni}{M}}}{n!} \frac{d^{n-1}}{dz^{n-1}} \left(e^{N\lambda_I(z-1)}\right)^{\frac{n}{M}} \Bigg|_{z=0} \qquad m = 1, \ldots, M-1 \tag{17}$$

The preceding argument leads to a set of $M-1$ linear equations for $\pi_k^x, k = 0, \ldots, M-1$.

$$\sum_{k=0}^{M-1} \pi_k^x (z_m^M - z_m^k) = 0 \qquad m = 1, \ldots, M-1 \tag{18}$$

If there is another equation, all M unknown coefficients $\pi_k^x, k = 0, \ldots, M-1$ are determined. The last equation can be obtained from the normalizing condition as

$$\sum_{k=0}^{M-1} \pi_k^x (M-k) = M - N\lambda_I \tag{19}$$

Let $\overline{X}$ be the average number of isochronous packets in the queue at the beginning of a cycle in steady state. It is given by

$$\overline{X} = \frac{dX(z)}{dz} \Bigg|_{z=1} \tag{20}$$

Also, let $\overline{X^h}, h = 1, \ldots, N-1$, be the average number of isochronous packets in the queue at the beginning of the $h+1$ th slot of a cycle in the steady state. These are given by

$$\overline{X^h} = \frac{dX^h(z)}{dz} \Bigg|_{z=1} = \begin{cases} h\lambda_I - h + \overline{X} + \sum_{k=1}^{h-1}(h-k)\pi_k^x & h = 1, \ldots, M \\ h\lambda_I - M + \overline{X} + \sum_{k=1}^{M-1}(M-k)\pi_k^x & h = M+1, \ldots, N-1 \end{cases} \tag{21}$$

Finally, by Little's theorem, the average waiting time of an isochronous packet in the steady state is given by

$$\frac{\overline{X} + \sum_{h=1}^{N-1} \overline{X^h}}{N\lambda_I} \tag{22}$$

4.2 Asynchronous Transfer Mode

Let us proceed to consider the asynchronous traffic. Note that it is influenced by the presence of the isochronous traffic.

From (3b) and (3d), the probability generating functions for Y_n and Y_n^h are given by

$$\begin{aligned} Y_n(z) &= e^{N\lambda_A(z-1)} Y_{n-1,N}(z) \\ Y_n^h(z) &= e^{h\lambda_A(z-1)} Y_{n,h}(z) \qquad h = 1, \ldots, N-1 \end{aligned} \tag{23}$$

In order to express the probability generating function for $Y_{n,h}$, we introduce some more auxiliary functions as follows.

$$X_n^{(h)}(z) := \sum_{k=0}^{h-1} P(X_n = k) z^k \qquad h = 1, \ldots, M \tag{24}$$

$$Y_n^{(h)}(z) := \sum_{k=0}^{h-1} P(Y_n = k) z^k \qquad h = 1, \ldots, N \tag{25}$$

$$D_{n,h}(z) := \begin{cases} X_n^{(h)}(z) + P(X_n \geq h) z^h & h = 1, \ldots, M \\ X_n^{(M)}(z) + P(X_n \geq M) z^M & h = M+1, \ldots, N \end{cases} \tag{26}$$

$$C_{n,h} := \begin{cases} \sum_{k=0}^{h-1} P(X_n = k) P(Y_n \leq h-k-1) \\ \qquad\qquad h = 1, \ldots, M \\ \sum_{k=0}^{M-1} P(X_n = k) P(Y_n \leq h-k-1) + P(Y_n \leq h-M-1) P(X_n \geq M) \\ \qquad\qquad h = M+1, \ldots, N \end{cases} \tag{27}$$

$$E_{n,h}(z) := \begin{cases} C_{n,h} z^h - \sum_{k=0}^{h-1} Y_n^{(h-k)}(z) P(X_n = k) z^k \\ \qquad\qquad h = 1, \ldots, M \\ C_{n,h} z^h - \left(\sum_{k=0}^{M-1} Y_n^{(h-k)}(z) P(X_n = k) z^k + Y_n^{(h-M)}(z) P(X_n \geq M) z^M \right) \\ \qquad\qquad h = M+1, \ldots, N \end{cases} \tag{28}$$

Thus the probability generating function of $Y_{n,h}$ is given by

$$Y_{n,h}(z) = \frac{Y_n(z) D_{n,h}(z) + E_{n,h}(z)}{z^h} \qquad h = 1, \ldots, N-1 \tag{29}$$

Let $Y(z)$ be the probability generating function for the number of asynchronous packets in the queue at the beginning of a cycle in the steady state. Let $Y^h(z)$ be the probability generating function for the number of asynchronous packets in the queue at the beginning of the $h+1$ th slot of a cycle in the steady state. In addition, $\pi_k^y, k = 0, \ldots, N-1$, is defined as the probability that the number of asynchronous packets in the queue is k at the beginning of a cycle in the steady state. Furthermore, $X^h(z), Y^h(z), D_h(z), C_h$, and $E_h(z)$ denote the functions corresponding to $X_n^h(z), Y_n^h(z), D_{n,h}(z), C_{n,h}$, and $E_{n,h}(z)$ in (24)–(28), where $P(X_n = k)$ and $P(Y_n = k)$ are replaced with π_k^x and π_k^y, respectively.

Let $D_N(z)$ be the probability generating function for the number of slots occupied by the isochronous packets transmitted in a cycle in the steady state. It is given by

$$D_N(z) = \sum_{k=0}^{M-1} \pi_k^x z^k + \left(1 - \sum_{k=0}^{M-1} \pi_k^x \right) z^M \tag{30}$$

Using $D_h(z)$ and $E_h(z)$, we can express $Y(z)$ and $Y^h(z)$ as

$$Y(z) = \frac{e^{N\lambda_A(z-1)}E_N(z)}{z^N - e^{N\lambda_A(z-1)}D_N(z)} \tag{31a}$$

$$Y^h(z) = \frac{e^{h\lambda_A(z-1)}\left(Y(z)D_h(z) + E_h(z)\right)}{z^h} \qquad h = 1, \dots, N-1 \tag{31b}$$

We can obtain the unknown coefficients $\pi_k^y, k = 0, \dots, N-1$, in the same say as in the case of the isochronous transfer mode. Namely, in the application of Rouché 's theorem to find the number of roots in the denominator of $Y(z)$ in (31a), we put

$$f(z) = z^N \tag{32}$$

$$g(z) = -e^{N\lambda_A(z-1)}D_N(z) \tag{33}$$

on $|z| = 1 + \epsilon$ for a small $\epsilon > 0$. Since $e^{N\lambda_A(z-1)}$ is the probability generating function of the Poisson distribution with rate $N\lambda_A$ and $D_N(z)$ is also the probability generating function, $g(z)$ is a probability generating function too. Thus we have

$$|g(z)| \leq 1 + \epsilon\left(N\lambda_A + \overline{D_N}\right) + o(\epsilon) \tag{34}$$

$$|f(z)| = (1+\epsilon)^N = 1 + N\epsilon + o(\epsilon) \tag{35}$$

where $\overline{D_N} = [dD_N/dz]_{z=1}$ is the average number of slots occupied by the isochronous packets transmitted in a cycle in the steady state. Therefore, $|g(z)| < |f(z)|$ if

$$\lambda_A + \frac{\overline{D_N}}{N} < 1 \tag{36}$$

This is the stability condition for the combination of isochronous and asynchronous traffic.

The average number of asynchronous packets in the queue at the beginning of a cycle in the steady state is given by

$$\overline{Y} = \left.\frac{dY(z)}{dz}\right|_{z=1} \tag{37}$$

The average number of asynchronous packets in the queue at the beginning of the $h+1$ th slot of a cycle in the steady state is given by

$$\overline{Y^h} = \left.\frac{dY^h(z)}{dz}\right|_{z=1} \qquad h = 1, \dots, N-1 \tag{38}$$

Finally, by Little's theorem, the average waiting time of an asynchronous packet in the steady state is given by

$$\frac{\overline{Y} + \sum_{h=1}^{N-1}\overline{Y^k}}{N\lambda_A} \tag{39}$$

5 Numerical Results

This section presents the numerical results for the average waiting times of isochronous and asynchronous packets in each queue in the steady state under the following conditions:

- Transmission speed : 100 Mbps
- Duration of a slot (unit of time) : 12.5 μseconds
- Number of slots of a cycle: $N = 10$
- Maximum number of the slots in a cycle available for the ITM : $M = 8$

Figure 3 plots the average waiting time of an isochronous packet in the queue in the steady state. It indicates that when the arrival rate approaches 0.8, the waiting time diverges infinitely. On the other hand, when the arrival rate is close to 0, the waiting time tends to 5.5 in unit of time, which is half the cycle length.

Figure 4 displays the average waiting time of an asynchronous packet in the queue in the steady state, parameterized by the arrival rate of isochronous packets. The waiting time of an asynchronous packet in the queue with the arrival rate of isochronous packets being 0.5, 0.3, and 0 is considered. According to this figure, the waiting time of an asynchronous packet tends to infinity when its arrival rate is close to one minus that of isochronous packets.

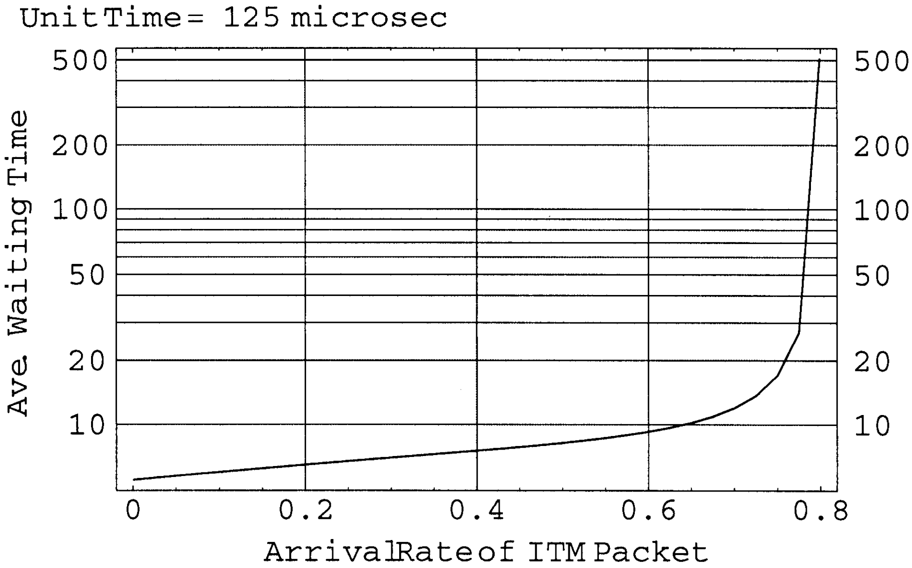

Figure 3: Average waiting time of an isochronous packet.

6 Concluding Remarks

We have modeled the IEEE 1394 high performance serial bus interface by a simple queueing model under some assumptions and calculated the average waiting time of an isochronous and an asynchronous packet in the buffer in the steady state. We have also shown some numerical results in order to estimate the performance of this serial bus

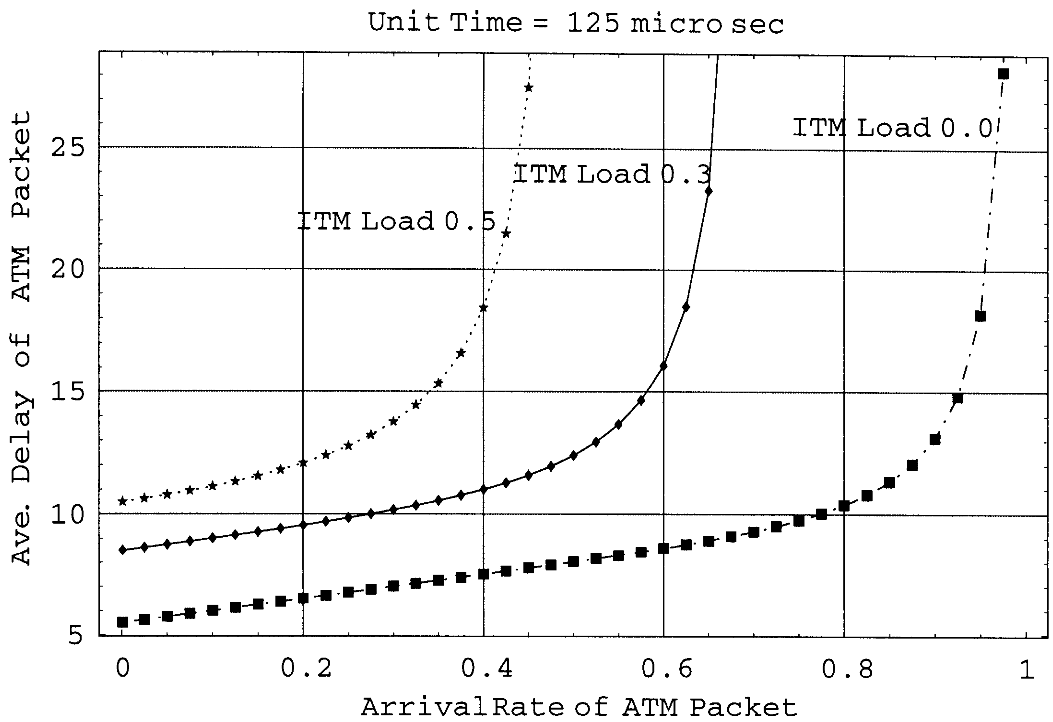

Figure 4: Average waiting time of an asynchronous packet.

roughly. However, our present model is far from the real system. First, it does not take the arbitration method into consideration. Second, we have assumed that a packet arriving in a cycle is not transmitted in the same cycle, and that it is transmitted after the next cycle. This is not the case in the real system. Therefore it remains us to revise the model so as to take these and other details into consideration.

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