PAPER

Optimal Packet Length in a Point-to-Point Communication System with a Layered Protocol Structure*

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SUMMARY The Optimal Packet Length (OPL) in packet-switched communication systems has been studied in the literature from various aspects. In this paper, we consider the trade-off between packet length and data transmission delay in a high-speed communication system. To simplify the analysis of the mean data transmission delay, the model is limited to a point-to-point communication system, in which each node complies with the OSI reference model. In order to study the relationship between the OPL and the number of modules performing each protocol, two model communication systems are discussed. In one each node contains two layered protocol modules, and in the other three. Moreover, for both models, the mean data transmission delay is analyzed for two cases depending on whether or not the DLC layer or the network layer performs retransmissions. After studying the OPL which minimizes the mean data transmission delay in each case, we discuss the relationships between the OPLs and the various protocol parameters.

key words: *optimal packet length, layered protocol, packet-switched communication system*

1. Introduction

Almost all communication network protocols are designed using layered architectures. A layered model is formed of a hierarchy of modules where each module performs some protocol function. Each module logically communicates with the corresponding peer module going through lower modules. The function of each module is thus to perform as a black-box with a direct connection to its peer module, and therefore input-output events to/from the black-box can be regarded as pairs of input request messages and corresponding response messages. This characteristic requires a proper model to evaluate the performance of a communication system with layered architecture. Let us consider the example of data transmission in a packet-switched communication system which complies with the OSI reference model.

In the OSI reference model, each layer has its own data format which the PDU (Protocol Data Unit). In a packet-switched network, the PDU is called a packet in the network layer and a frame in the DLC layer. Figure 1 illustrates the data format below the transport layer. Incoming data to the network layer should be split into packet-sized segments by the transport layer if its length is larger than the maximum data size that the network layer can process, and the data is transmitted separately segment by segment. These packet-sized segments are reassembled in the transport layer of the receiver node. At each layer of the sender node, the incoming, descending data is wrapped with the PCI (Protocol Control Information) of the layer and this PCI will be removed by the corresponding layer of the receiver node. Figure 2 shows the transmission flow for a segment S1 into the transport peer module. In order to send S1 to its peer transport layer, the transport layer wraps a Tr-PCI around S1, which is then sent through to the network peer module. Furthermore, the network layer peer module in turn uses the lower DLC peer modules. The network and the DLC procedures end by receiving corresponding response messages CR (P) and CR (F) from their peer modules. Note that the transmission of CR (P) also needs to use the DLC modules. After the transport layer of the receiver node receives the data from the network layer, it removes Tr-PCI while returning a corresponding response message CR (S) to finish the transport process. CR (S) is sent

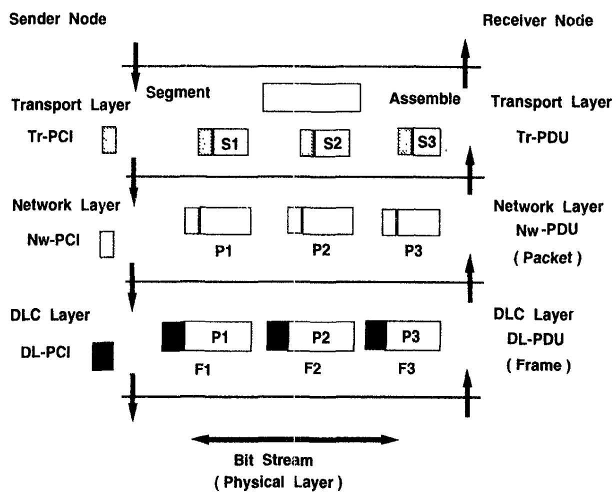

Fig. 1 Data format in the OSI model.

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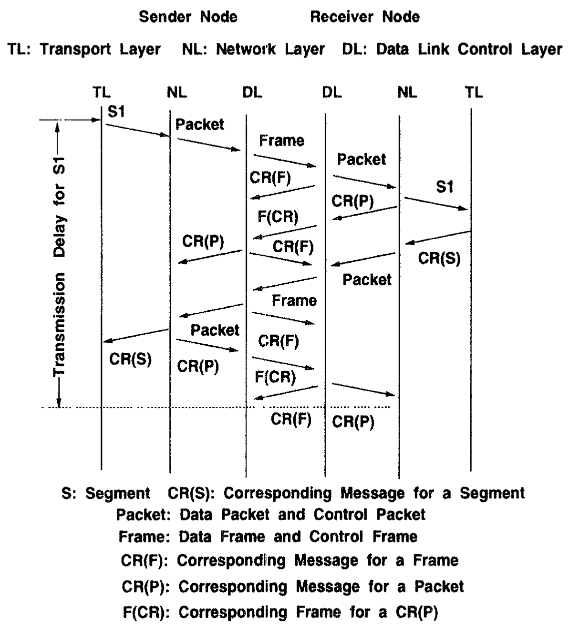

Fig. 2 Data transmission procedure.

back in the same way as S1. If an error is detected at any of these layers, the associated sending layer should retransmit the message according to some retransmission scheme.

The above flow control description shows that at least two kinds of delay should be included in the packet transmission delay model for a layered protocol structure. One is the delay of the data itself caused by queuing and processing through the modules of each layer. Therefore this should be analyzed by a multi-queue model instead of a single queue. Another delay is caused by the corresponding response messages which accompany the data. In the above example, there are four corresponding frames, two corresponding packets and one corresponding segment transferred and processed between the layer modules. These corresponding messages increase as the number of layers increases. In addition, besides the above corresponding messages, every layer module may also generate other control messages, such as congestion control packets and retransmission control frames, to control the overall data transmission. These control messages are also queued and processed together with the data; delay of and due to these control messages should be included in a complete analysis.

Recently, several approaches have been proposed to evaluate the performance of a layered model. An approximation algorithm has been presented to analyze the performance of a multi-layered network with sliding window protocols [1]. The approximation uses an interesting queuing theory technique to reduce multi-layered network hierarchy to a single queue in order to simplify the analysis. An iterative algorithm has been introduced to analyze the performance of a two-layer LAN model [2], and the same method has been employed to analyze an interconnected LAN model [3]. However, all of these studies have ignored the delay caused by the control messages and corresponding messages. A simulation method which includes the delay of the corresponding response messages is developed in [4]. Considering the three kinds of delay, a tandem M/M/1 queuing model has been proposed to evaluate the mean data message response delay for a high speed point-to-point system [5] and a LAN system [6]. Because the analytical results of [5] agree well with measurements of a real system (see Appendix B), the model can be regarded as a superior one for evaluating the performance of layered protocol systems. In this paper, we apply the basic layered model proposed in [5] to our model of packet transmission in order to study data transmission delay and the OPL which minimizes the data transmission delay.

Since the maximum packet length is an important parameter which influences system performance in packet-switched networks, the OPL has been studied in many papers [7]–[16], however, these discussions on packet transmission have been limited to a single protocol layer. We focus on the relationship between the OPL and layered protocol parameters. Since error-free transmission is assumed in [5], we first analyze the data transmission delay including retransmission. For convenience of descriptive terminology, the OSI model is chosen here over other protocols. The lower three layer modules related with retransmission—transport layer, network layer, DLC layer (the physical layer is ignored because there is no software control there) are studied for their effect on data transmission. Since one of our purposes is to study the relationship between the OPL and the number of modules implementing the protocol, the communication system is discussed for two separate models: a two-layered model and a three-layered model. Furthermore, for both models, the mean data transmission delay is discussed for two cases—either the retransmission procedure is carried out only at the DLC layer module or only at the network-layer module. The OPL is theoretically proven to exist in each case and is shown by several numerical examples.

The paper is organized in the following way: The model definition and description of parameters are given in Sect. 2. The mean data transmission delay and the OPL in the two-layered model are studied in Sect. 3 and those in the three-layered model are similarly studied in Sect. 4. Then, Sect. 5 presents several numerical examples of the OPL for the two models. Finally discussions and conclusions are provided in Sect. 6.

2. Modeling of the Communication System

2.1 Point-to-Point Communication Model

The communication system consists of two nodes in an interactive processing environment. Multiple users use

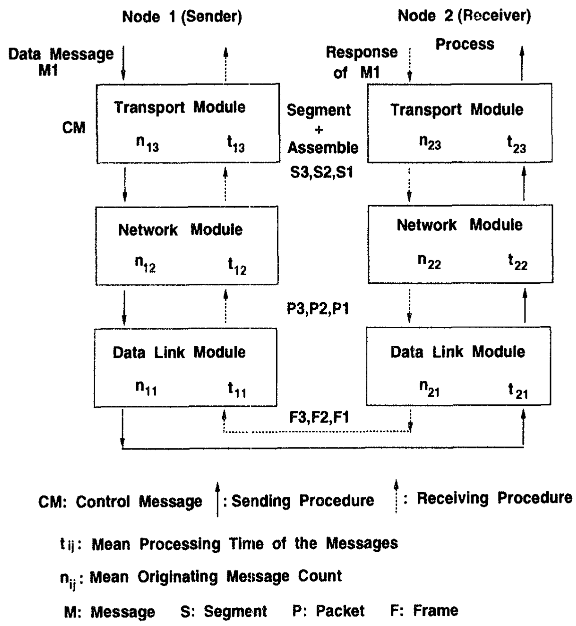

Fig. 3 The structure of the three-layered communication model.

the sender node to transmit data messages to the receiver node simultaneously. The receiver node sends an corresponding message back after a data message is received. In this paper, a two-layered communication model is studied as well as a three-layered communication model. Figure 3 shows the three-layered point-to-point model in which each node consists of the transport, network and DLC modules each executing functions of the corresponding layer of the OSI reference model. The two-layered communication model consists of only the network layer and the DLC layer, in this case the data is assumed to have been split into data segments before entering the network layer and segmentation and assembly delay are assumed to be ignorable when compared with the transmission delay.

Each layer module has a queue holding the data, the corresponding response messages and control messages as shown in Fig. 2. The delay time including protocol processing time at each module is the sum of the total processing time and the waiting time of all messages.

2.2 Assumptions

Error detection is assumed to be carried out in the same layer which does the retransmission. Only random errors are assumed to be detected in the system. An Ack is sent back when no error is detected. Although some detection methods like CRC can correct a limited number of bit errors, most real communication systems retransmit the error data without forward error correction. In this model, the sending layer starts the retransmission if an Ack is not received within a random time-out interval. Control messages are short enough that error free operation is assumed.

The following assumptions are required for the analysis of the data transmission delay.

There are three kinds of control messages entering the queue of a module. These include the messages generated in the layer, the messages received from the next higher layer, and the messages received from the next lower layer (or in the case of the lowest layer, messages incoming from the network). There are also three kinds of output messages: messages expired from service, messages sent to the next higher layer and messages sent to the next lower layer. We assume that the three kinds of input messages have the same mean service time for each module and the following assumptions are made:

- Poisson arrival of the data
- Exponential service time at each module
- Message independence

2.3 Description of Parameters

The mean data transmission delay T is defined as the average time between some data arriving at the sender node and the corresponding response message being received back. In the two-layered model, T is defined as the sum of the transmission delays of all the segmented packets. The parameters and variables for analyzing the mean data transmission delay are defined as follows:

λ: Mean arrival rate of data incoming to the communication system

L: Mean data length

j: Layer module number (1 at the lowest DLC layer, increasing by one at each higher layer)

h_j: The length of the PCI at the j-th layer module

x: The maximum packet length, which equals the PCI length h_2 of the network layer plus the maximum transport data segment length

p_e: Average BER (Bit Error Rate)

a: A positive constant dependent upon p_e such as $a = -\ln(1 - p_e)$

N_x: Mean number of transmissions for an x-bit-long packet.

i: Node number (1 for the sender and 2 for the receiver)

t_{ij} : Mean service time of messages at the j-th layer module of node i

n_{ij} : Number of originating messages generated at the

j-th layer of node i due to a layer $(j+1)$ data message transmission

n_j : $n_j = n_{1j} + n_{2j}$

c_{ij} : The total number of messages processed in the j-th layer of node i for a successful $(j+1)$ data packet transmission in the two-layered model or in the three-layered model for a successful data message transmission.

3. Two-Layered Communication System

3.1 Mean Data Transmission Delay

3.1.1 Mean Number of Transmissions

For a random error, the probability that an x-bit-long data packet may have at least one error in the transmission is

$$p = 1 - (1 - p_e)^{(x+h_1)} \tag{1}$$

where p_e equals average BER and $(x+h_1)$ is the average data frame length transmitted on the physical link. The probability that a packet can be transferred successfully at the k-th transmission is $P_k = p^{k-1}(1-p)$. Therefore, the mean number of transmissions N_x for an x-bit-long data packet in this model is

$$\begin{aligned} N_x &= \sum_{k=1}^{\infty} kP_k \\ &= (1-p)(1 + 2p + 3p^2 + 4p^3 + \cdots) \\ &= \frac{1}{(1-p)} = (1-p_e)^{-(x+h_1)} \end{aligned} \tag{2}$$

3.1.2 Analysis of Mean Data Transmission Delay

The mean data transmission delay is the sum of the total delay times for all of the messages processed through all of the modules. The delay through each module is in turn composed of both message wait and processing time. From the assumptions of Sect. 2.2, the messages into each module are put into an M/M/1 queue [17]. According to M/M/1 queuing theory, the mean delay time W_{ij} for each message at the j-th layer of node i can be calculated from the arrival rate λ_{ij} of messages and the mean processing time t_{ij} per message.

$$W_{ij} = \frac{t_{ij}}{1 - \lambda_{ij} t_{ij}} \tag{3}$$

where the following conditions are required by M/M/1 theory for $i, j = 1, 2$.

$$1 - \lambda_{ij} t_{ij} > 0. \tag{4}$$

The arrival rate λ_{ij} of messages at each layer module is the arrival rate of segmented packets multiplied by the number of the messages c_{ij} for a single packet transmission. λ_{ij} can be calculated as:

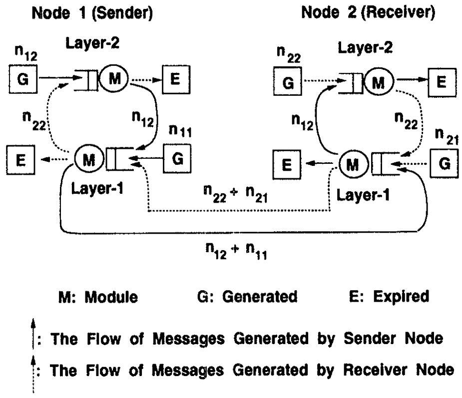

Fig. 4 The number of messages per data packet transmission processed in each module without retransmission.

$$\lambda_{ij} = \frac{L}{(x - h_2)} \lambda c_{ij}. \tag{5}$$

where λ is the arrival rate of data with mean length L, and $L/(x-h_2)$ is the number of data packets into which the L-bit-long data is segmented.

Substituting Eq. (5) into Eq. (3) gives

$$\begin{aligned} T &= \frac{L}{x - h_2} \sum_{i=1}^{2} \sum_{j=1}^{2} c_{ij} W_{ij} \\ &= \frac{L}{x - h_2} \sum_{i=1}^{2} \sum_{j=1}^{2} \frac{c_{ij} t_{ij}}{1 - \lambda_{ij} t_{ij}}. \end{aligned} \tag{6}$$

Figure 4 lets us count the number of messages that each module handles per data packet transmission when retransmissions are not included. The number of messages processed in the DLC layer of the sender node c_{11} is the sum of the number of messages n_{11} generated at its own layer, n_{12} transferred from the network layer and $(n_{22} + n_{21})$ received from the receiver node.

The number of messages c_{ij} increases when retransmission occurs. Since the increase differs depending on which layer executes the retransmission, we analyze c_{ij} into two cases, one in which the retransmission is performed by the DLC layer and one in which network layer handles retransmissions.

3.1.3 Retransmission at the DLC Layer

Because the network layer is error free, there is no influence upon the input number of messages at the network module. In the DLC layer module of the sender node, an x-bit-long data packet needs to be transmitted N_x times before it is received correctly. Thus, the messages generated by the DLC layer increase to $N_x n_{11}$, and the messages $(n_{22} + n_{21})$ sent to the DLC layer from the receiver node also increase to $(N_x n_{22} + n_{21})$. Similarly, we get the number of messages c_{ij} processed at the j-th layer of node i for a successful data packet transmission to be

$$c_{12} = c_{22} = n_{12} + n_{22} = n_2 \tag{7}$$

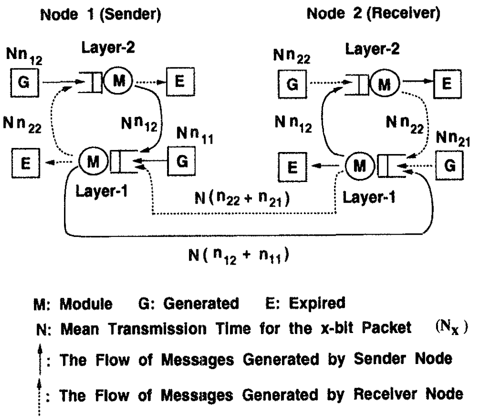

Fig. 5 The number of messages per data packet transmission processed in each module in the case of retransmission at the network layer.

$$
\begin{aligned}
c_{11} = c_{21} &= n_{12} + N_x n_{11} + n_{22} + N_x n_{21} && (8)\\
&= n_2 + N_x n_1 && (9)
\end{aligned}
$$

where $n_j = n_{1j} + n_{2j}$. The mean data transmission delay T can be obtained by substituting the above c_{ij} into Eq. (6). T is

$$
\begin{aligned}
T &= \sum_{i=1}^{2}\left[\frac{Lb_{i2}^2}{x - h_2 - b_{i2}^2 L\lambda}\right.\\
&\quad \left. + \frac{L(b_{i1}^2 + N_x b_{i1}^1)}{x - h_2 - (b_{i1}^2 + b_{i1}^1 N_x)L\lambda}\right] && (10)\\
&= \sum_{i=1}^{2}(T_{i2} + T_{i1}), && (11)
\end{aligned}
$$

where $b_{ij}^k = t_{ij} n_k$ and we rewrite the two terms in the brackets of Eq. (10) as T_{i2} and T_{i1}.

The following relations are required for $i = 1, 2$ from Eq. (4).

$$
\begin{array}{lcll}
x - h_2 & - & b_{i2}^2 L\lambda & > 0\\
x - h_2 & - & (b_{i1}^2 + N_x b_{i1}^1)L\lambda & > 0.
\end{array} \qquad (12)
$$

3.1.4 Retransmission at the Network Layer

Here for a packet retransmission, the DLC layer also generates additional messages. Figure 5 lets us count the number of the messages processed at each layer for a successful data packet transmission. Therefore, c_{ij} can be seen to be:

$$
\begin{aligned}
c_{12} &= c_{22} = N_x(n_{12} + n_{22}) = N_x n_2 && (13)\\
c_{11} &= c_{21} = N_x(n_{12} + n_{22} + n_{11} + n_{21}) && (14)\\
&= N_x(n_2 + n_1). && (15)
\end{aligned}
$$

Substituting this into Eq. (6), the mean data transmission delay T for this case becomes

$$
T = \sum_{i=1}^{2}\sum_{j=1}^{2}\frac{N_x b_{ij}^u}{x - h_2 - N_x b_{ij}^u L\lambda} = \sum_{i=1}^{2}\sum_{j=1}^{2} T_{ij}^u \qquad (16)
$$

where $b_{ij}^u = t_{ij} c_{ij} / N_x$ and the following conditions are necessary for $i = 1, 2$ from Eq. (4).

$$
x - h_2 - N_x b_{ij}^u L\lambda > 0. \qquad (17)
$$

3.2 Proof that an OPL Exists

The mean data transmission delay T is a function of the average BER p_e, the average data length L, the data arrival rate λ, system parameters n_{ij} and t_{ij}, and the data packet length x. The optimal packet length is defined as that x which minimizes the mean data transmission delay T when all the other parameters are held constant.

In an actual system, the number of segmented data packets has a positive integer value. We shall assume x to be a continuous value to simplify our analysis by replacing the discrete model with a continuous one. This assumption does not violate the generality of our model. The OPL for each retransmission layer case is discussed below.

3.2.1 Proof in the Case of Retransmission at the DLC Layer

Based on Eq. (11), the first derivative of each term T_{ij} with respect to x is

$$
\begin{aligned}
T'_{i2} &= -\frac{Lb_{i2}^2}{(x - h_2 - b_{i2}^2 L\lambda)^2} && (18)\\
T'_{i1} &= \frac{LN_x b_{i1}^1[a(x - h_2) - 1] - Lb_{i1}^2}{\left[x - h_2 - (b_{i1}^2 + N_x b_{i1}^1)L\lambda\right]^2}. && (19)
\end{aligned}
$$

It is easy to see that T'_{i2} is a monotonic increasing function of x for $i = 1, 2$, and thus $T''_{i2} > 0$.

We use the function f_y introduced in the Appendix A to prove that $T''_{i1} > 0$. Let y be $(x - h_2)$, then the function f_y is transformed into the following:

$$
f_{x-h_2} = \frac{N_x(1 - p_e)^{h_2} b_1[a(x - h_2) - 1] - b_0}{\left[b_2(x - h_2) - [b_0 + N_x b_1(1 - p_e)^{h_2}]b_3\right]^2}, \qquad (20)
$$

and $f'_y > 0$ results in $f'_{x-h_2} > 0$. Because b_0, b_1, b_2, b_3 are arbitrary positive constants, $(Lb_{i1}^2,\ Lb_{i1}^1(1 - p_e)^{-h_2},\ 1,\ \lambda)$ can be substituted for (b_0, b_1, b_2, b_3), which makes f_{x-h_2} equal the function of T'_{i1} given in Eq. (19). Therefore, T'_{i1} is a special case of the function f_{x-h_2}, which therefore results that $T''_{i1} > 0$.

The second derivatives of T_{ij} for $i, j = 1, 2$ have all been proven to be positive, thus $T'' > 0$ is obtained as required. This result shows that the function T is convex and an OPL truly exists when the DLC layer handles the retransmission.

Ideally, the OPL is the packet length x such that $T'_x = 0$. Since it is difficult to solve for the OPL from $T' = 0$, several numerical results on the OPL will be presented in Sect. 5.1 to elucidate the relationships between the OPL and the other parameters.

3.2.2 Proof for the Case of Retransmission at the Network Layer

By calculating the first derivative of the mean data transmission delay for this case from Eq. (16), we have

$$T_{ij}^{u\prime} = \frac{LN_x b_{ij}^u [a(x-h_2)-1]}{\left[x-h_2-b_{ij}^u N_x L\lambda\right]^2}. \tag{21}$$

f_{x-h_2} in Eq. (20) can be transformed into the same function as Eq. (21) if the positive arbitrary constants (b_0, b_1, b_2, b_3) are substituted for by $(0, Lb_{ij}^u(1-p_e)^{-h_2}, 1, \lambda)$. Thus, each $T_{ij}^{u\prime}$ is a special case of the function f_{x-h_2}, and $T_{ij}^{u\prime\prime} > 0$ for $(i, j = 1, 2)$. Hence, an OPL also exists when the retransmission is carried out at the network layer.

It is easy to find from Eq. (21) that $T_{ij}^{u\prime} = 0$ when the mean packet length takes on the following value:

$$x = -\frac{1}{\ln(1-p_e)} + h_2.$$

We have that the OPL is given by x if the mean data length is longer than $-1/\ln(1-p_e)$. Otherwise, the OPL becomes $L+h_2$ because T is convex. Consequently, the OPL in the two-layered model where the retransmission is carried out at the network layer is shown to be:

$$x_{OPL} = \min\left(L, -\frac{1}{\ln(1-p_e)}\right) + h_2. \tag{22}$$

Note that the above OPL depends only on the mean data length L, average BER p_e and the PCI length of the network layer h_2.

4. Three-Layered Communication System

In the two-layered communication model, packet segmentation and reassembly delays are ignored. In this section, these kinds of delays are included in the transport layer. The mean data transmission delay and the OPL will be studied by an approach similar to the previous section.

4.1 Mean Data Transmission Delay

Each module has an M/M/1 queue as in the two-layered model. The mean data transmission delay T is the sum of the delay time of all the messages processed at each module for each data transmission, that is

$$T = \sum_{i=1}^{2}\sum_{j=1}^{3} c_{ij} W_{ij} \tag{23}$$

where c_{ij} is the average total number of messages processed at the j-th layer of node i per data message, W_{ij} denotes the mean delay time per message, which can be calculated from the arrival rate of messages λ_{ij} and the mean processing time t_{ij} per message. From M/M/1 theory, we have

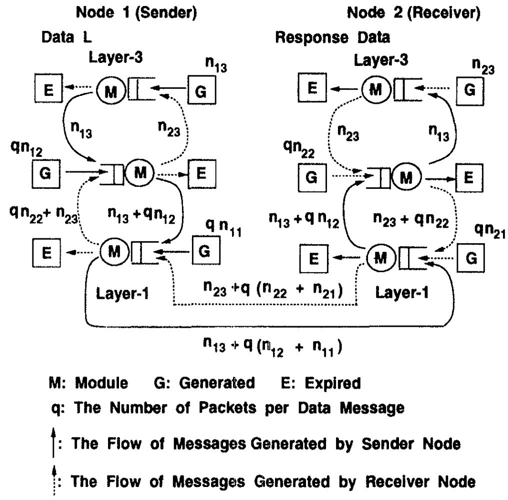

Fig. 6 The number of messages per data message transmission processed in each module without retransmission.

$$W_{ij} = \frac{t_{ij}}{1-\lambda_{ij}t_{ij}} \tag{24}$$

where

$$1-\lambda_{ij}t_{ij} > 0. \tag{25}$$

The arrival rate of messages λ_{ij} is given by

$$\lambda_{ij} = \lambda c_{ij}.$$

Substituting λ_{ij} into Eq. (23) results in

$$T = \sum_{i=1}^{2}\sum_{j=1}^{3} \frac{c_{ij}t_{ij}}{1-\lambda c_{ij}t_{ij}}. \tag{26}$$

Let q be the average number of packets per data message, i.e.,

$$q = \frac{L}{x-h_2-h_3} \tag{27}$$

where h_2 and h_3 are the PCI lengths of the network layer and the transport layer.

In the case of no retransmission, the number of messages handled at each module for a single data transmission can be counted from Fig. 6. Since $n_{ij}(i, j = 1, 2)$ represents the number of messages generated for a packet transmission at the network or the DLC layer module, n_{ij} messages are generated q times during a single data transmission. Therefore, the number of messages sent to the DLC layer from the network layer becomes $n_{i3}+qn_{i2}$ and the number sent to opposite node's DLC layer becomes $q(n_{i2}+n_{i1})+n_{i3}$.

In the three-layered model, the mean number of transmissions N_x for an x-bit-long packet takes on the same value as that of the two-layered model. We next consider c_{ij} for the two cases.

4.1.1 Retransmission at the DLC Layer

There is no increase in the input number of messages

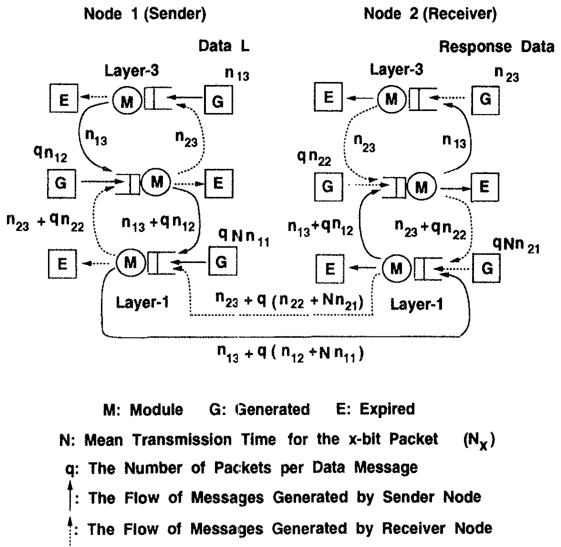

Fig. 7 The number of messages per data message transmission processed in each module in the case of retransmission at the DLC layer.

at the transport and the network layers. As can be seen from Fig. 7, the number of messages generated in the DLC layer increases to qN_xn_{i1}. This results in the number of the messages sent to the DLC layer of the opposite node being increased to $n_{i3}+q(n_{i2}+N_xn_{i1})$. Consequently, the number of messages c_{ij} handled at the j-th layer of node i for a successful data transmission is

$$c_{13} = c_{23} = n_{13}+n_{23} = n_3 \tag{28}$$

$$c_{12} = n_{13}+n_{23}+q(n_{12}+n_{22}) = n_3+qn_2 \tag{29}$$

$$\begin{aligned} c_{11} &= n_{13}+n_{23}+q(n_{12}+n_{22})+qN_x(n_{11}+n_{21}) \\ &= n_3+qn_2+qN_xn_1. \end{aligned} \tag{30}$$

Substituting the above c_{ij} into Eq. (26), we get

$$\begin{aligned} T &= \sum_{i=1}^{2}\left[\frac{n_3t_{i3}}{1-\lambda n_3t_{i3}}+\frac{(n_3+qn_2)t_{i2}}{1-(n_3+qn_2)t_{i2}\lambda}\right. \\ &\quad \left.+\frac{[n_3+q(n_2+N_xn_1)]t_{i1}}{1-[n_3+q(n_2+N_xn_1)]t_{i1}\lambda}\right] \end{aligned} \tag{31}$$

$$= \sum_{i=1}^{2}(T_{i3}+T_{i2}+T_{i1}) \tag{32}$$

where T_{i3}, T_{i2}, T_{i1} identify the bracketed terms in Eq. (31), and each denominator of T_{i3}, T_{i2} and T_{i1} is required to be positive by Eq. (25).

4.1.2 Retransmission at the Network Layer

In this case, $qn_{ij}(i,j=1,2)$ messages should be generated N_x times for each successful data transmission by the network layer and the DLC layer. Therefore, the number of the messages $qn_{ij}(i,j=1,2)$ generated at the network layer and the DLC layer increases to qN_xn_{ij} respectively. Accordingly, the number of the messages sent from the network layer module to the DLC layer changes to $n_{i3}+qN_xn_{i2}$ and the number sent to the DLC layer module of the opposite node becomes $n_{i3}+qN_x(n_{i2}+n_{i1})$. Hence, the number of the messages c_{ij} processed at the j-th layer of node i for a successful data message transmission is obtained as

$$c_{13} = c_{23} = n_{13}+n_{23} = n_3 \tag{33}$$

$$\begin{aligned} c_{12} &= n_{13}+n_{23}+qN_x(n_{12}+n_{22}) \\ &= n_3+qN_xn_2 \end{aligned} \tag{34}$$

$$\begin{aligned} c_{11} &= n_{13}+n_{23}+qN_x(n_{12}+n_{22}+n_{11}+n_{21}) \\ &= n_3+qN_x(n_2+n_1). \end{aligned} \tag{35}$$

Using the above c_{ij} in Eq. (24), we obtain

$$\begin{aligned} T &= \sum_{i=1}^{2}\left[\frac{n_3t_{i3}}{1-\lambda n_3t_{i3}}+\frac{(n_3+qN_xn_2)t_{i2}}{1-(n_3+qN_xn_2)t_{i2}\lambda}\right. \\ &\quad \left.+\frac{n_3+qN_x(n_2+n_1)t_{i1}}{1-[n_3+qN_x(n_2+n_1)]t_{i1}\lambda}\right] \end{aligned} \tag{36}$$

where again the denominator of each bracketed term should be positive from Eq. (25).

4.2 Proof that an OPL Exists

4.2.1 Proof for the Case Retransmission at the DLC Layer

Substituting q into Eq. (31), the mean data transmission delay can be rewritten as:

$$T_{i3}=\frac{b_{i3}^3}{1-b_{i3}^3\lambda} \tag{37}$$

$$T_{i2}=\frac{1}{\lambda}\left[\frac{x-h_2-h_3}{(1-b_{i2}^3\lambda)(x-h_2-h_3)-b_{i2}^2L\lambda}-1\right] \tag{38}$$

$$\begin{aligned} T_{i1}=\frac{1}{\lambda}&\left[\frac{x-h_2-h_3}{(1-b_{i1}^3\lambda)(x-h_2-h_3)-(b_{i1}^2+N_xb_{i1}^1)L\lambda}\right. \\ &\left.-1\right] \end{aligned} \tag{39}$$

where $t_{ij}n_k$ is written as b_{ij}^k, and the denominator of each term is required to be positive. Since T_{i3} is independent of x, $T_{i3}''=0$. Calculation of the first derivative of T_{i1} and T_{i2} gives

$$T_{i2}'=-\frac{Lb_{i2}^3}{[(1-b_{i2}^3\lambda)(x-h_2-h_3)-b_{i2}^2L\lambda]^2} \tag{40}$$

$$T_{i1}'=\frac{LN_xb_{i1}^1[a(x-h_2-h_3)-1]-Lb_{i1}^2}{\left[(1-b_{i1}^3\lambda)(x-h_2-h_3)-(b_{i1}^2+N_xb_{i1}^1)L\lambda\right]^2} \tag{41}$$

where $a=-ln(1-p_e)$.

It is obvious that T_{i2}' is a monotonic increasing function of x, $T_{i2}''>0$.

Again the function f_y from the Appendix A is reused to prove that $T_{i1}''>0$. Let y be $(x-h_2-h_3)$, f_y

is transformed into following function $f_{x-h_2-h_3}$ of x.

$$\frac{N_x(1-p_e)^{h_2+h_3}b_1[a(x-h_2-h_3)-1]-b_0}{\left[b_2(x-h_2-h_3)-[b_0+N_xb_1(1-p_e)^{(h_2+h_3)}]b_3\right]^2}. \quad (42)$$

We have that $f'_{x-h_2-h_3} > 0$ because $f'_y > 0$. $f_{x-h_2-h_3}$ becomes the same function as T'_{i1} if the positive arbitrary constants b_0, b_1, b_2, b_3 are substituted for by $(Lb^2_{i1}, Lb^1_{i1}(1-p_e)^{-h_2-h_3}, 1-b^3_{i1}\lambda, \lambda)$. Thus, $T''_{i1} > 0$.

Since $T''_{i3} = 0$, and both T''_{i2} and $T''_{i1} > 0$, the result is that $\sum_{i=1}^{2}\sum_{j=1}^{3} T''_{ij} = T'' > 0$. Therefore, an OPL also exists in this case. Numerical results for the OPL will be presented in the Sect. 5.2.

4.2.2 Proof for the Case of Retransmission at the Network Layer

Denoting by T_{i3}, T_{i2}, T_{i1} the bracketed terms of Eq. (36), we obtain the first derivatives of T_{ij} as:

$$T'_{i3} = 0 \quad (43)$$

$$T'_{i2} = \frac{LN_xb^2_{i2}[a(x-h_2-h_3)-1]}{[(1-b^3_{i2}\lambda)(x-h_2-h_3)-N_xb^2_{i2}L\lambda]^2} \quad (44)$$

$$T'_{i1} = \frac{LN_x(b^2_{i1}+b^1_{i1})[a(x-h_2-h_3)-1]}{[(1-b^3_{i1}\lambda)(x-h_2-h_3)-N_x(b^2_{i1}+b^1_{i1})L\lambda]^2}. \quad (45)$$

Obviously, $T''_{i3} = 0$. By using $f'_{x-h_2-h3} > 0$ derived from the previous section, we now prove that T''_{i2} and T''_{i1} both have positive values.

If (b_0, b_1, b_2, b_3) are replaced by the positive constants $(0, Lb^2_{i2}(1-p_e)^{-h_2-h_3}, 1-b^3_{i2}\lambda, \lambda)$, the function f_{x-h_2-h3} becomes identical with T'_{i2} of Eq. (44). Furthermore, Eq. (44) transforms into T'_{i1} of Eq. (45) if b^2_{i2} is substituted for by $b^2_{i1}+b^1_{i1}$. That is, both Eq. (44) and Eq. (45) are special cases of $f_{x-h_2-h_3}$, thus both T''_{i2} and T''_{i1} are positive. This shows that T is a convex function of the mean packet length x. Thus an OPL also exists when retransmission is carried out at the network layer module.

Note that $\sum_{i=1}^{2}\sum_{j=1}^{3} T'_{ij} = T' = 0$ at

$$x = -\frac{1}{\ln(1-p_e)} + h_2 + h_3$$

from Eqs. (43), (44) and Eq. (45). With the same reasoning as in Sect. 3.2.2, the OPL is found to be

$$x_{OPL} = \min\left(L, -\frac{1}{\ln(1-p_e)}\right) + h_2 + h_3. \quad (46)$$

5. Numerical Results and Discussion

In the case where the retransmission is carried out at the network layer, the OPL is simply determined by the average BER p_e, the mean data length L and the PCI length h_2 of the network layer and h_3 of the transport layer. The results of the analysis have been shown in Eq. (22) for the two-layered model, and Eq. (46) for the three-layered model. As it is difficult to solve directly the OPL when the DLC layer module performs the retransmission, numerical examples of the OPL are presented in this section to elucidate the relationships between the OPL and and the various parameters in each model. Furthermore, by comparing the results of the two models and the two cases, the relationship between the OPL and the number of layered modules implementing the protocol is discussed as well as the relationship between the OPL and the location of the layer executing the retransmission.

5.1 Numerical Examples of the OPL for the Two-Layered Model

A numerical analysis is employed to calculate the OPL minimizing the mean data transmission delay of Eq. (11). Figures 8, 9 and 10 show the OPL as a function of the various system parameters. All are calculated under the same conditions of low traffic arrival rate, and with PCI's lengths of 18 bytes for the network layer, 24 bytes for the DLC layer and the number of the originating control messages at each layer is $(n_{11}, n_{12}, n_{21}, n_{22}) = (4, 2, 4, 2)$.

With conditions that the average BER $p_e = 10^{-3}$ and the mean processing time of control messages at each layer module $(t_{11}, t_{12}, t_{21}, t_{22})$ being $(0.13\times10^{-3}\,\mathrm{sec}, 0.15\times10^{-3}\,\mathrm{sec}, 0.09\times10^{-3}\,\mathrm{sec}, 0.11\times10^{-3}\,\mathrm{sec})$, Fig. 8 shows the relationship between the OPL and the mean data length, for the case of data arrival rates λ of 6 and 90 per minute. When the mean data length is smaller than the maximum length of a packet, the OPL is nearly equal to that of the mean data length. Thus, the OPL increases linearly as the mean data length increases, and it reaches a maximum value at the point where the mean data length is about 1300 bits for $\lambda = 6$

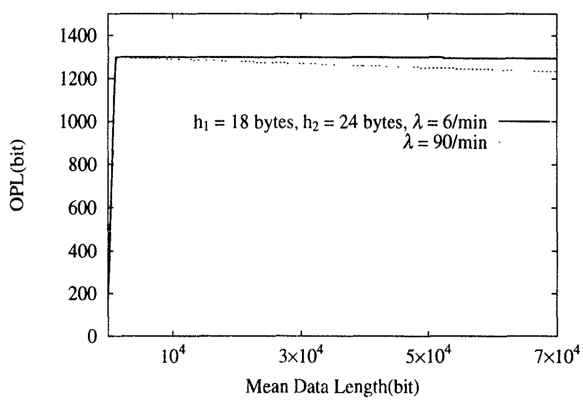

Fig. 8 OPL vs. Mean data length.

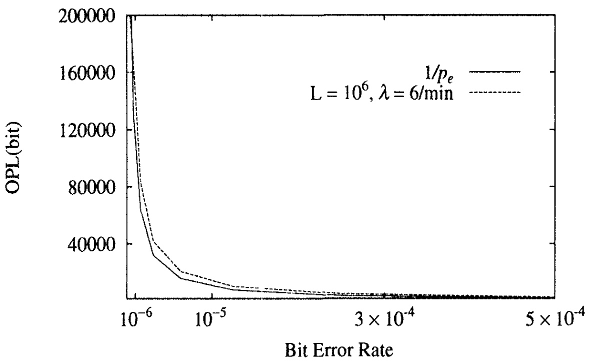

Fig. 9 OPL vs. Bit Error Rate.

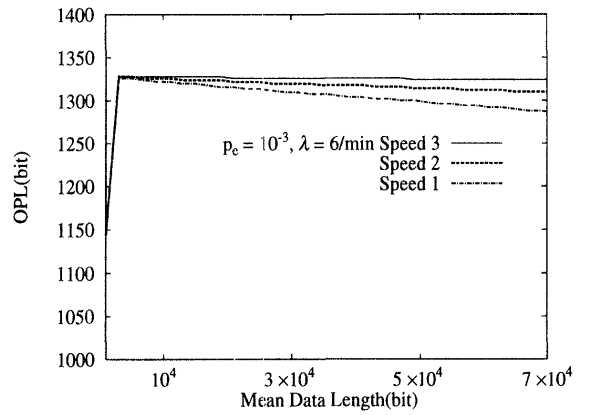

Fig. 10 OPL vs. Node's processing speed.

per minute. Then it decreases as the mean data length becomes longer than 1300 bits. The degradation of the OPL size is caused by the increasing retransmission of error packets.. The more the data is segmented into packets, the greater the possibility of retransmission for error packets.

Under the same system parameters, Fig. 9 shows the relationship between the OPL and the average BER when the data length is 10^6 bits and the arrival rate λ is 6 per minute. Comparing this with the curve of $1/p_e$, we can see the OPL is in inverse proportion to the average BER p_e.

Figure 10 shows the OPL for different node processing speeds for $p_e = 10^{-3}$ and $\lambda = 6$ per minute. The mean processing times t_{ij} of the curves marked "speed 3" and "speed 2" are three times faster, and two times faster than that of the communication system represented by the "speed 1." As the node's processing speed becomes slower, we see that the OPL also becomes shorter.

Let us evaluate the OPL in order to compare it for the two retransmission cases in the two-layered model. It can been seen from Eqs. (18) and (19) that the first derivative of T remains negative if $(x - h_2) \leq -1/\ln(1 - p_e)$. As the OPL is x such that $T'_x = 0$, the OPL must be longer than $-1/\ln(1 - p_e) + h_2$. However, if the mean data length L is shorter than this, the OPL becomes $L + h_2$ from the nature of the convex function. Thus, in the case that the DCL layer executes the retransmission, the OPL is no shorter than the $\min(L, -1/\ln(1 - p_e)) + h_2$. It is already known from Eq. (22) that the OPL is $\min(L, -1/\ln(1 - p_e)) + h_2$ when retransmission is carried out at the network layer. Therefore, the OPL gets longer when the retransmission procedure is carried out in the lower DLC layer.

5.2 Numerical Examples of the OPL for the Three-Layered Model

The relationships between the OPL and the mean data length, average BER and node's processing time can be studied with Eq. (32). In order to compare the results with the two-layered model, the parameters of the DLC and the network layer are kept the same as those in the corresponding figures for the two-layered model. All OPLs are calculated with a PCI length of the transport layer of 24 bytes and the number of originating control messages generated in the transport layer is 2 messages for both the sender node and the receiver node.

Figure 11 shows the relationship between the OPL and the mean data length when the mean message processing times of the transport layer are set to 0.15 sec for t_{13} and 0.13 sec for t_{23}. The other parameters are the same as in Fig. 8. The previous OPL for the two-layered model under the arrival rate of $\lambda = 90$ per minute is also presented here for comparison. Similar relationships between the mean data length and the OPL in the two-layered model can also be seen in the three-layered model as well as in the relationship between the OPL and the data arrival rate. Comparing the OPL with that of the two-layered model, we see that the OPL is longer in the three-layered model. One of the reasons is that the extra 24 bytes of transport layer's PCI is included in the OPL. Comparison of the pure data length included in the OPL of the two models will be shown later.

Under the same system parameters described in Fig. 11, Fig. 12 illustrates the relationship between the OPL and the average BER of the three-layered model along with that of the two-layered model. The average data length is 10^6 bits and the arrival rate λ is 6 per minute. It shows that the OPL in the three-layered model is also highly affected by the average BER, just as it was the two-layered model.

Figure 13 shows the OPL as parameterized by the node's processing speed when $\lambda = 60$ per minute and the average BER and other system parameters are the same as those of Fig. 11. The mean processing times t_{ij} of the curves represented by "speed 3" and "speed 2" are also three times, and two times faster than that of the communication system represented by "speed 1." Again we see that the OPL of three-layered model, becomes shorter when the node's processing speed becomes slower.

When the DLC layer performs the retransmission, the first derivative of the mean data transmission delay T takes on a negative value when the packet length x

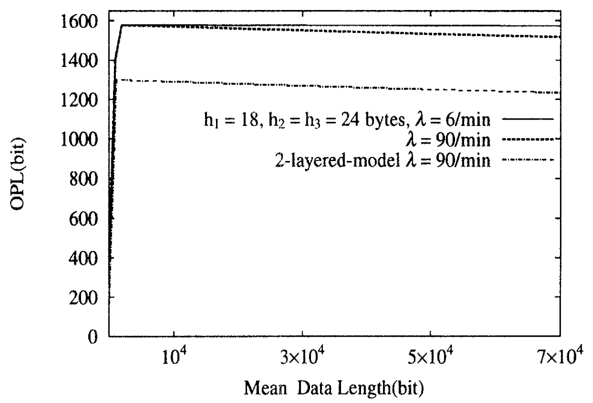

Fig. 11 OPL vs. Mean data length.

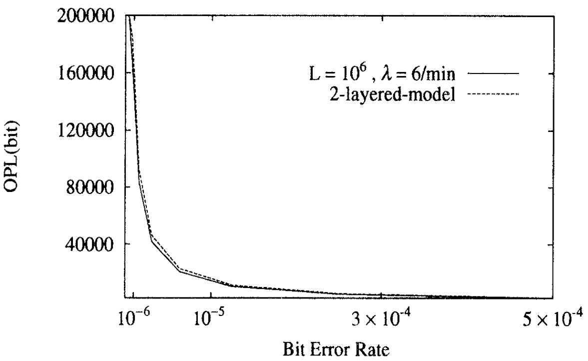

Fig. 12 OPL vs. Bit Error Rate.

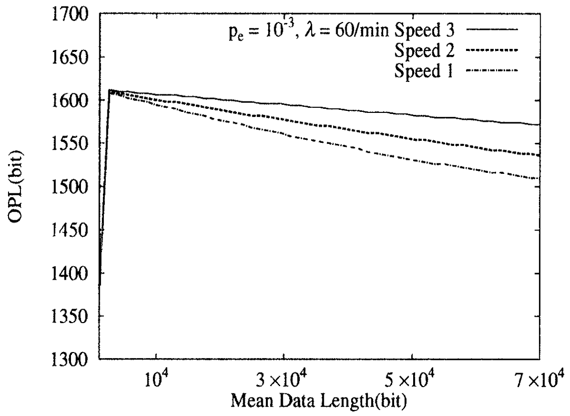

Fig. 13 OPL vs. Node's processing speed.

is shorter than $-1/\ln(1-p_e)+h_2+h_3$ from Eq. (40) and Eq. (41). With the same reasoning presented in Sect. 4.2, the OPL is no shorter than $\min(L,-1/\ln(1-p_e))+h_2+h_3$. On the other hand, when the retransmission is carried out by the network layer, the OPL is $\min(L,-1/\ln(1-p_e))+h_2+h_3$ according to Eq. (46). Therefore, in the three-layered model, the same conclusion can be obtained as with the two-layer model that the OPL gets shorter as the location of the layer performing the retransmission becomes higher.

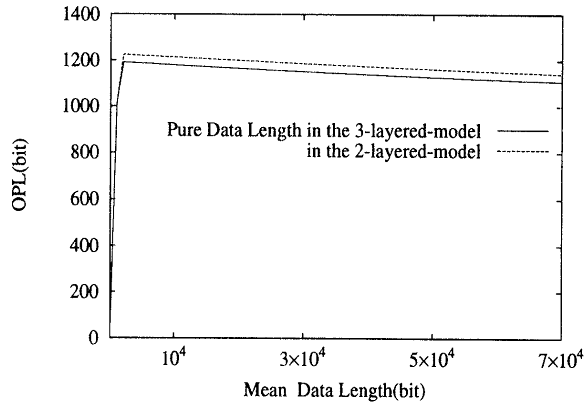

Fig. 14 The pure data length included in the OPL.

5.3 Comparison of the Two Models

Generally, efficiency and throughput of data transmission becomes better as the packet length gets longer. On the other hand, the transmission efficiency becomes worse if the number of protocol layers performing the protocol functions gets larger. This is because that each layer adds its own PCI before sending the data to the next lower layer. Since the OPL discussed above includes this PCI overhead, next we study the pure data length (after elimination of all overhead) included in the OPL.

In the case where network layer executes the retransmission, the OPL in the three-layered model is given by $\min(L,-1/\ln(1-p_e))+h_2+h_3$ from Eq. (46) while in the two-layered model it is $\min(L,-1/\ln(1-p_e))+h_2$ from Eq. (22). The pure data is thus exactly the same in the two models. Therefore, as compared with the two-layered model, the data transmission efficiency becomes worse in the three-layered model as the effective OPL is not longer.

When retransmission is implemented in the DLC layer, it is already seen from Fig. 11 that the OPL for the three-layered model is longer than that for the two-layered model under otherwise similar conditions and parameters. The pure data length contained within the OPL of Fig. 11 is illustrated in Fig. 14. It can be seen that the pure data length in the OPL of the two-layered model is longer than that in the three-layered model. Thus, it can be also concluded that the data transmission efficiency gets worse if the number of layers performing the protocols becomes larger.

6. Conclusion

In this paper, we have studied the mean data transmission delay and the OPL in a point-to-point packet-switched communication system based on the OSI reference model. The communication system has been modeled by a two-layered model and a three-layered model. The mean data transmission delay and the OPL were discussed in two separate cases depending on whether the DLC layer or the network layer performs the error retransmission function. Several numerical results have been presented to elucidate the relationships between the OPL, the average BER, the mean data length, the arrival rate and other various system parameters.

Several conclusions can be drawn from our study. First, our results indicate that the OPL is mostly affected by the BER of the transmission media and the mean data length. The maximum packet length in a high speed communication system should take a value not shorter than the sum of $\min(L, -1/\ln(1-p_e))$ and the PCI lengths used from the network layer to the highest layer. Second, the data transmission efficiency gets worse when a transport layer is added to the two-layered model. Third, in the same model, the OPL becomes shorter as the location of the layer module performing the retransmission function is raised while the mean data transmission delay gets longer. In short, the fewer the number of layer modules implementing the protocol, and the lower the location of the layer where the retransmission is executed, the better the data message transmission efficiency gets and the shorter the mean data transmission delay becomes. On the other hand, our results also show that the OPL is much easier to be obtained in the case that the retransmission procedure is carried out in the network layer. In that case, we can realize an optimal system structure by using an OPL which depends on fewer system parameters.

The data transmission in this paper is discussed for a single direction, however, it is easy to expand the model to a bidirectional data transmission system such as a client-server communication system. Moreover, although this work has been focused on the OSI reference model, a similar analysis can easily be applied to other hierarchical protocol models. However, burst error conditions, flow control messages and processing and communication systems where the retransmission procedures are performed at more than one layer all remain to be investigated by further research.

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Appendix A: Proof that $f_y' > 0$

We define f_y a function of y by:

$$f_y = \frac{N_y b_1(ay-1) - b_0}{[b_2 y - (b_0 + N_y b_1)b_3]^2} \tag{A·1}$$

where $y > 0$, $N_y = (1-p_e)^{-(y+h_1)}$, p_e, h_1, a are fixed constants defined in Sect. 2.3 and b_0, b_1, b_2, b_3 are arbitrary positive constants which satisfy

$$b_2 y - (b_0 + N_y b_1)b_3 > 0. \tag{A·2}$$

Calculating the first derivative of f_y yields

$$f_y' = \frac{g_1 - 2g_2g_3}{[b_2y - (b_0 + N_yb_1)b_3]^3} \quad (A\cdot 3)$$

where

$$g_1 = a^2N_yb_1y[b_2y - (b_0 + N_yb_1)b_3]$$
$$g_2 = b_2 - aN_yb_1b_3$$
$$g_3 = N_yb_1(ay - 1) - b_0. \quad (A\cdot 4)$$

We have $g_1 > 0$ from the requirement of Eq. (A· 2). Since $a > 0$ by definition in Sect. 2.3, g_2 is a monotonic decreasing function of y while g_3 is a monotonic increasing function of y. Because they are continuous functions, y_1 and y_2 must exist such that

$$g_2(y_1) = 0, \quad g_3(y_2) = 0.$$

Namely,

$$b_2 - aN_{y_1}b_1b_3 = 0 \quad (A\cdot 5)$$
$$N_{y_2}b_1[ay_2 - 1] - b_0 = 0. \quad (A\cdot 6)$$

Next we want to show that $y_2 \leqq y_1$. Solving Eq. (A· 2) for b_2y_2/b_3 and substituting into Eq. (A· 6) we obtain $N_{y_2}b_1ay_2 = N_{y_2}b_1 + b_0 < b_2y_2/b_3$. Eliminating y_2 gives

$$aN_{y_2}b_1b_3 < b_2 \quad (A\cdot 7)$$

and rewriting Eq. (A· 5) yields

$$aN_{y_1}b_1b_3 = b_2.$$

We see that $N_{y_2} < N_{y_1}$. But since N_y is a monotonic increasing function of y, we have shown that $y_2 < y_1$. Hence, g_2g_3 is negative in the ranges of $y \leqq y_2$ and $y \geqq y_1$, and Eq. (A· 3) results in $f_y' > 0$.

Finally, we need to show $f_y' > 0$ in the range $y_2 < y < y_1$. Note that for all values of y in this range $(g_2(y) > 0)$ and $(g_3(y) > 0)$, that is

$$b_2 - aN_yb_1b_3 > 0 \quad (A\cdot 8)$$
$$N_yb_1(ay - 1) > b_0. \quad (A\cdot 9)$$

Thus,

$$aN_yb_1b_3 < b_2 \quad (A\cdot 10)$$
$$ay > 1, \quad ayN_yb_1 > b_0 + N_yb_1. \quad (A\cdot 11)$$

$ay > 1$ because a, b_0, b_1, b_2 and N are all positive. Expanding $(g_1 - 2g_2g_3)$ from the definitions of Eq. (A· 4) we get

$$\begin{aligned} g_1 - 2g_2g_3 = N_yb_1\Big[& b_2a^2y^2 - a^2y(b_0 + N_yb_1)b_3 \\ & -2(b_2 - aN_yb_1b_3)(ay - 1) \\ & +2\frac{b_0}{N_yb_1}(b_2 - aN_yb_1b_3)\Big]. \end{aligned} \quad (A\cdot 12)$$

From Eq. (A· 8) we have that the last term of Eq. (A· 12) is positive. If we drop it from the right hand side, Eq. (A· 12) becomes an inequality.

If we multiply Eq. (A· 11) by a^2yb_3, we see that since $a^2y(b_0 + N_yb_1)b_3$ in the first line of Eq. (A· 12) is smaller than $a^2yayN_yb_1b_3$, the inequality will be preserved if we substitute the large term. Then Eq. (A· 12) becomes,

$$\begin{aligned} \frac{g}{N_yb_1} &> b_2a^2y^2 - a^2y^2aN_yb_1b_3 - 2b_2ay + 2b_2 \\ &\quad +2a^2yN_yb_1b_3 - 2aN_yb_1b_3 \\ &= b_2[(ay-1)^2 + 1] + aN_yb_1b_3[-a^2y^2 + 2ay - 2] \\ &= b_2[(ay-1)^2 + 1] + aN_yb_1b_3[-1 - (ay-1)^2] \\ &= [(ay-1)^2 + 1](b_2 - aN_yb_1b_3) \\ &> 0 \end{aligned} \quad (A\cdot 13)$$

where $g = g_1 - 2g_2g_3$.

Hence, the first derivative of f_y has been proven to be strictly positive for all y.

Appendix B: Results from Pape [5]

Figure A· 1 shows the real communication system used to validate the analytical results. A TIP (Terminal Interface Processor) host connected with 30 terminals and a TSS host communicates each through an optical link. User messages input from the terminals are processed in the TSS host and their response messages should be sent back.

The communication protocols of the TIP and the TSS hosts were implemented by four layer modules. The mean message processing time and the number of control messages of each layer used by the analytical results were calculated by the built-in hardware RPs with functions of measurements, statistics and calculations of the transactions from every terminal. The mean response times in normal traffic loads were measured and calculated when the students were doing programming exercises at terminals, while those in the high traffic loads were measured by using simulated environments through a traffic generator.

Figure A· 2 shows the mean response times of the measured and the analytical results. It can be seen that analytical results agree well with the measured data when the traffic load is not heavy.

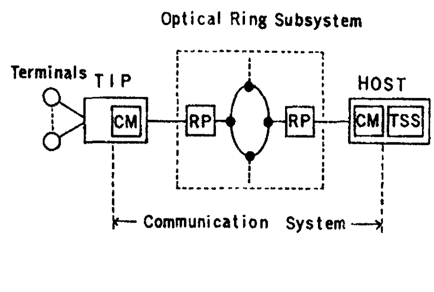

Fig. A· 1 The communication system used for measurements.

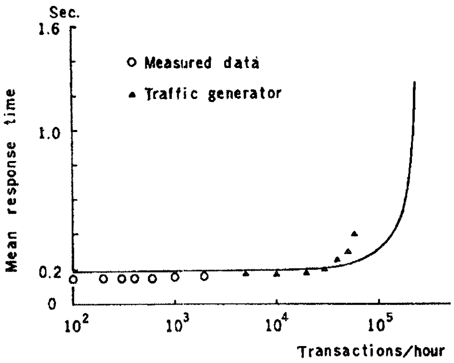

Fig. A·2 The analytical and measured results of mean response time.

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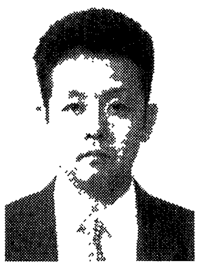

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