論 文

X. 25 Protocol의 성능 분석

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Performance Analysis of The CCITT X.25 Protocol

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요 약 본 논문에서는 packet switching network의 국제 표준 접속 protocol인 CCITT X.25 protocol의 성능을 분석하며 특히 X.25 protocol 의 유통 제어 방식에 대하여 분석한다. Protocol의 성능 분석은 normalized channel throughput, mean transmission time과 transmission efficiency를 사용하며 이들은 window 크기, T_1 및 T_2 값 그리고 message 길이 등과 같은 주어진 protocol parameter의 함수로 표시된다. 먼저 protocol 서비스에 따른 입력 데이타의 서비스 특성과 piggybacked acknowledgment를 하는 sliding window flow control 방식에 대하여 discrete-time Markov chain을 사용하여 연구한다. Protocol의 성능은 link layer 및 packet layer에 대하여 각기 독립적으로 분석하며 분석결과를 통하여 각 protocol parameter의 영향을 조사한다. 수치적인 분석 결과로 부터 채널 서비스 환경에 따른 protocol parameter의 최적치를 찾을 수 있는데 window크기는 고속채널의 경우 7 이상이 되는 것이 바람직 하며, T_1 timer 값은 채널의 전송 유실이 많은 경우 신중히 선택되어져야 하며 보통의 경우에는 1초 정도가 타당하다. T_2 parameter는 transmission efficiency의 개선에 있어 약간의 효과를 미치나 그리 크지는 않다.

ABSTRACT In this paper, we analyze the performance, particularly the flow control mechanism, of the CCITT X.25 protocol in a packet-switched network. In this analysis, we consider the link and packet layers separately, and investigate the performance in three measures; normalized channel throughput, mean transmission time, and transmission efficiency. Each of these measures is formulated in terms of given protocol parameters such as window size, T_1 and T_2 values, message length, and so forth. We model the service procedure of the input traffic based on the flow control mechanism of the X.25 protocol, and investigate the mechanism of the sliding window flow control with the piggybacked acknowledgment scheme using a discrete-time Markov chain model. With this model, we study the effect of variation of the protocol parameters on the performance of the X.25 protocol. From the numerical results of this analysis one can select the optimal values of the protocol parameters for different channel environments. It has been found that to maintain the transmission capacity satisfactorily, the window size must be greater than or equal to 7 in a high-speed channel. The time-out value, T_1, must carefully be selected in a noisy channel. In a normal condition, it should be in the order of 1 s. The value of T_2 has some effect on the transmission efficiency, but is not critical.

I. INTRODUCTION

The X.25 protocol recommended by CCITT (International Telegraph and Telephone Consultative Committee) is being widely used as one of the most important protocols for synchronous data transmission in public packet-switched networks. It is a standard device-independent interface be-

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tween packet networks and user devices operating in the packet mode.[1]

The X.25 interface between the data terminal equipment (DTE) and the data circuit-terminating equipment (DCE) consists of three distinct layers of control procedure; the physical layer, the link layer (or the frame layer), and the packet layer.[1] Each of those layers functions independently of the other layers, but a failure at a lower layer may affect the operation of higher layers. The physical layer specifies the use of a duplex, point-to-point synchronous circuit, thus providing a physical transmission path between the DTE and the network. The link layer specifies the data link control procedure that is compatible with the high-level data link control (HDLC) procedures specified by the international standard organization (ISO).[2] In the X.25, these procedures are referred to as the balanced link access procedure (LAPB).[1] The significance of the link layer is that it provides the packet layer with an error-free link between the DTE and the network. The packet layer is the highest layer of the X.25 interface. It specifies the manner in which control information and user data are structured into packets. It also allows a single physical circuit to support communications to other DTE's concurrently.

So far, the performance of the control procedure of the X.25 protocol has been studied through the analysis of the HDLC procedure, which is similar to that of the link layer protocol. The performance of the HDLC was analyzed extensively by Bux et al.[3] It was also investigated in different conditions by Wang[4] and Labetoulle et al.[5] The effect of the window size for an error-free link was studied by Yu and Majithia.[6]

In this paper, we analyze the flow control mechanism of the X.25 protocol. Particularly, we are concerned with the selection of the protocol parameter values that optimize the performance. In this work, we consider two layers of the protocol (that is, the link and packet layers) separately, and use three performance measures, that is, normalized channel throughput, mean transmission time, and channel efficiency. Each of these measures is represented as a function of protocol parameters such as window size, data length, T_1 and T_2 timers, and so forth. We first obtain the service procedure of the input traffic operating in X.25, and also investigate the mechanism of the sliding window flow control with the piggybacked acknowledgment scheme using a discrete-time Markov chain model. Then, the three performance measures will be formulated in terms of the given protocol parameters. The normalized channel throughput is first determined as a function of the probability of blocking transmission due to the window flow control. The mean transmission time is then investigated by using the window control mechanism and the concept of virtual transmission time suggested by Bux et al.[3] In addition, the transmission efficiency is formulated as a function of the protocol parameters such as data length and T_2 values.

Following this introduction, in Section II we obtain the service characteristics of the control procedure, and also investigate the window mechanism of the X.25 protocol. In Section III, we describe the three performance measures in terms of the given protocol parameters. In Section IV we present and discuss the numerical results. Finally, we make conclusions in Section V.

II. SERVICE PROCEDURE AND WINDOW MODEL OF THE X.25 PROTOCOL

In this section, we model the service procedure of the input traffic based on the flow control mechanism of the X.25 protocol, and investigate the sliding window mechanism of each layer.

To analyze the flow control mechanism of the X.25 protocol, we make the following assumptions:

- The communication link is full-duplex.
- The buffer storage is infinite.
- The operating condition of the protocol is normally in a data transfer phase.
- The data stream is mutually independent and exponentially distributed.

A. Service Procedure of the Link Layer

The stations at both ends of a link have various characteristic patterns of operation for information transmission. The link service procedure can be characterized by the flow control mechanism and also by the error recovery procedure. In this section, we are particularly concerned with the flow control mechanism which is a sliding window protocol with the piggybacked acknowledgment scheme. When an information frame is ready for transmission, it can be used to piggyback the window information of the incoming frame. In the case where a station has no more information frame to send, an incoming frame is acknowledged by a receive ready (RR) frame. The outgoing acknowledgment can temporarily be delayed for a better use of piggybacking, and the maximum limit of the acknowledgment delay is specified by a value of T_2 as a system parameter.[1]

For modeling the service procedure we make the following basic assumptions. The arrival of messages is assumed to be a Poisson process with the rate λ, and the service time is assumed to be exponentially distributed. Then, the inter-departure process is also Poisson by Burke's theorem.[7] Here, although the inter-departure process of the link layer is not Poisson due to the additional control frame, we can assume that under the appropriate conditions, the inter-departure process is Poisson at the rate of λ'. Fig. 1 shows the two cases of acknowledging the incoming information frames. In this figure, r is the acknolwedgment delay time of the link layer at the node B, and r′ is the residual life time of the incoming information frame.[8] It can be shown that the upper bound of the acknowledgment delay time r is given by T_2 value.

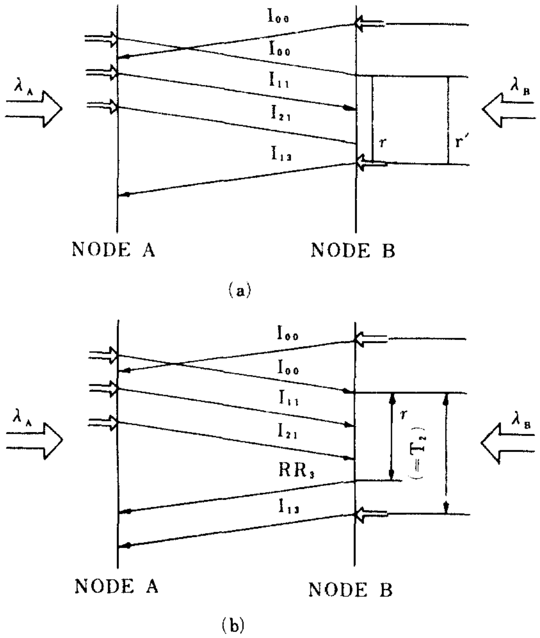

Fig. 1 Acknowledgment procedure of the link layer
(a) The case of using the piggybacked acknowledgment
(b) The case of being acknowledged by an RR-frame.

The Laplace transform Fr′(s) of the residual life time r′ is given by [9]

$$F_r'(s)=\frac{1-F(s)}{s\,\bar{m}} \tag{1}$$

where F(s) is the Laplace transform of the interarrival time distribution (assumed to be exponentially distributed) at the node B, and $\bar{m}$ is the mean interarrival time. Thus, the probability density $f_r(t)$ of the acknowledgement delay time r is given by

$$f_r(t)=\begin{cases}\dfrac{\lambda_B e^{-\lambda_B t}}{1-e^{-\lambda_B T_2}}, & \lambda_B \neq 0,\ T_2 \neq 0,\\ & 0 \leq t \leq T_2\\ 0, & \text{otherwise,}\end{cases} \tag{2}$$

We now consider the probability that the control frames (i.e., RR, REJ frames, etc.) are generated. In general, control frames are generated in one of the following three cases; the case that the piggybacked information frame to be sent does not exist during T_2 time after receiving an information frame, the case that the receive window is on the lower window edge, and the case that there occur channel errors. If we assume that the channel error probability P_B is much less than one, the acknowledgment probability P_B [ack] of the incoming information frames at the node B can be represented as

$$P_B[\text{ack}] \simeq \frac{e^{-\lambda_B T_2}}{\lambda_A T_2 + 1}(1 - P_{r\phi}) + P_{r\phi} + P_B. \tag{3}$$

In (3) the factor $\left(\frac{1}{\lambda_A T_2 + 1}\right)$ is the ratio of the number of the acknowledgment frame and the number of the incoming information frames during T_2 time. It indicates the efficiency of the acknowledgment frame by the piggybacking scheme. Also, $P_{r\phi}$ is the probability that the receive window width is zero (This will be considered in Section II-C.). Similarly, the acknowledgment probability P_A [ack] at the node A is given by

$$P_A[\text{ack}] \cong \frac{e^{-\lambda_A T_2}}{\lambda_B T_2 + 1}(1 - P_{r\phi}) + P_{r\phi} + P_B. \tag{4}$$

Now, if we model the link layer handling an additional control frame in addition to information frames as an M/M/1 queueing system, the inter-departure rates λ'_A and λ'_B can be represented, respectively, as

$$\lambda'_A \cong \lambda_A + \lambda_B P_A[\text{ack}] \tag{5}$$

$$\lambda'_B \cong \lambda_B + \lambda_A P_B[\text{ack}]. \tag{6}$$

Note that in (5) and (6) we have used the superposition theorem of Poisson process.[9]

B. Service Procedure of the Packet Layer

For convenience of analysis, we assume the following in the packet layer. First, every logical channel of multiple virtual circuits is assumed to be mutually independent. Second, it is assumed that the function of the link layer for data transmission is solely to offer a transmission channel for the packet layer.

In this section, we consider a single error-free logical channel. The flow control mechanism of the packet layer is the sliding window flow control with the piggybacked acknowledgment scheme. It is similar to that of the link layer except that there is no acknowledgment due to the time-out of the T_2 time. In the packet layer, acknowledgment is made using the piggybacked information packet and an RR-packet. Without the piggybacked information packet, the sliding window of the packet layer becomes a fixed one. The probability that the acknowledgment packet (that is, the RR packet) is generated is determined by the receive window process, and is equal to the probability $P_{pr\phi}$ that the receive window is on the lower window edge (see Section II-D).

C. Window Model of the Link Layer

In this section, we consider the mechanism of sliding window flow control at the link layer. An important parameter under consideration is the window width which is the number of outstanding (unacknowledged) information frames. In operation of the protocol, the window width is represented as the difference between V(S) (which is a send-state variable) and the last value of N(R) (which is the receive sequence number) received.[1] Fig. 2 shows the mechanism of the window process of the link layer. Here, we consider two kinds of the window process; the receive window process and the send window process.

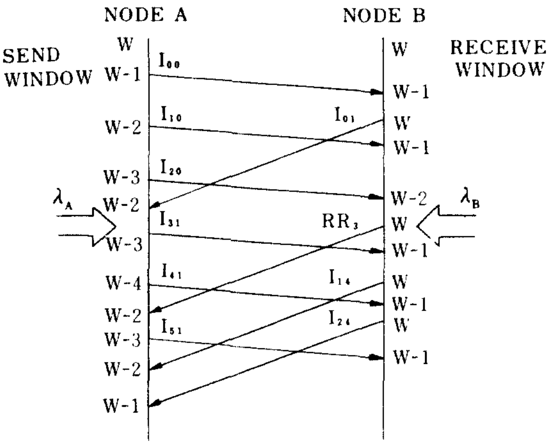

Fig. 2 Window process of the link layer.

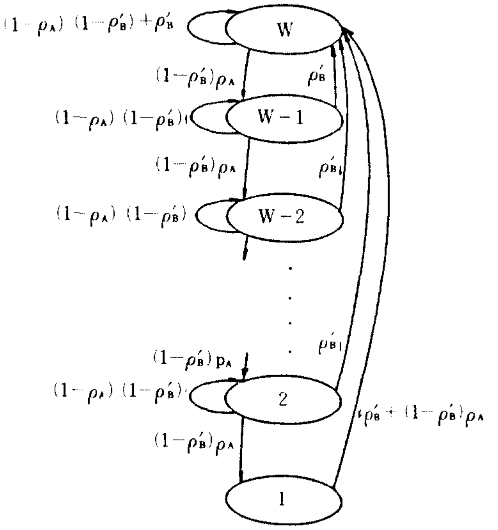

Fig. 3 A discrete-time Markov chain model of the receive window process of the link layer.

First, let us consider the mechanism of the receive window process. Initially, the receive window width is equal to the window size W. Whenever receiving an information frmae, the receive window width decrements by one; and whenever sending the acknowledgment, the receive window width returns to the initial state W. The operation of the receive window process can be modeled as a discrete-time Markov chain. This is shown in Fig. 3. In this figure, ρ_A is the utilization of an information frame in the direction from the node A to B, and ρ'_B is the total link utilization including the acknowledgment frame in the direction from the node B to A. The receive window decrements by one with the probability $(1-\rho'_B)\rho_A$ with which the incoming link is active and there is no acknowledgment traffic. When there exists an acknowledgment with the probability ρ'_B, the receive window returns to the initial state W. When an information frame is received, the receive window whose width has been 1 becomes zero. In this case, an acknowledgment is immediately returned and the receive window returns to the initial state. From the state-transition diagram of Fig. 3, we can obtain a solution for this process in the steady state. From the conservation of flow, the state probability of the receive window process in equilibrium is given by

$$P_{ri}=\frac{\dfrac{\rho'_B}{(1-\rho'_B)\rho_A}\left\{1+\dfrac{\rho'_B}{(1-\rho'_B)\rho_A}\right\}^{i-1}}{\left\{1+\dfrac{\rho'_B}{(1+\rho'_B)\rho_A}\right\}^{W}-1}$$

$$1 \leqq i \leqq W \qquad (7)$$

where P_{ri} is the probability that the receive window width is in the i-th state. The probability $P_{r\phi}$ (see Section II-A) is given by

$$P_{r\phi}=\frac{(1-\rho'_B)\rho_A}{(1-\rho'_B)\rho_A+\rho'_B}P_{r1}$$

$$=\frac{\dfrac{\rho'_B}{(1-\rho'_B)\rho_A+\rho'_B}}{\left\{1+\dfrac{\rho'_B}{(1-\rho'_B)\rho_A}\right\}^{W}-1} \qquad (8)$$

Next, we consider the mechanism of the send window process. Whenever an information frame is sent, the send window width decrements by one; and whenever an acknowledgment is received, the send window width increments by the number of information frames correctly received at the other node, which is equal to the difference between the receive sequence number N(R) of the acknowledgment and the last value of N(R) received. Fig. 4 shows a discrete-time Markov chain model of the send window process at the node A. One may note that this is similar to a G/M/1 Markov chain.[8] In this figure, it is seen that the send window width decrements by one with the probability $(1-\rho'_B)\rho_A$ that the outgoing link is active and there is no acknowledgment. When an acknowledgment is received with the probability ρ'_B, the send window width increments by the number of information frames correctly received at the other node. In Fig. 4, $q_i(k)$ is the probability that when the send window width is in the i-th state and an acknowledgment is received, the number of information frame correctly received at the other node is k+1. It is represented as

$$q_i(k)=\int_0^\infty \binom{W-1-i}{k}(1-e^{-\lambda_A t})^k(e^{-\lambda_A t})^{W-1-i-k}\cdot f_r(t)\,dt \qquad (9)$$

$$0\leqq i\leqq W-1,$$

$$0\leqq k\leqq W-1-i$$

where $\binom{a}{b}=\frac{a!}{b!(a-b)!}$, $f_r(t)$ is the probability density of acknowledgment delay time r given by (2), $e^{-\lambda_A t}$ is the probability that the frame to be sent is not yet received at the other node within time t.[1] In the steady state, the probability P_{Si} that the send window width is in the i-th state satisfies the following balanced flow equations:

$$\{(1-\rho'_B)\rho_A+\rho'_B\sum_{k=0}^{W-1-i}q_i(k)\}P_{Si}$$
$$=(1-\rho'_B)\rho_A P_{Si+1}+\rho'_B\sum_{k=0}^{i-1}q_k(i-1-k)P_{SK}, \qquad (10)$$

$$\rho_A P_{SW}=\rho'_B\sum_{k=0}^{W-1}q_k(W-1-k)P_{SK}, \qquad (11)$$

$$\rho'_B P_{S\emptyset}\sum_{k=0}^{W-1}q_0(k)=(1-\rho'_B)\rho_A P_{S1}, \qquad (12)$$

$$\sum_{k=0}^{W}P_{SK}=1, \qquad (13)$$

In a matrix form, the above equations may be written as

$$\mathbf{Q}\mathbf{P}=\mathbf{B} \qquad (14)$$

where $\mathbf{P}=[P_S, P_{S1},\cdots,P_{SW}]^t$, $\mathbf{Q}$ is a $(W+1)\times(W+1)$ matrix represented by

$$Q=\begin{bmatrix} 1 & 1 & 1\cdots\cdots\cdots 1 & 1 & 1 \\ \rho'_B\sum_{k=0}^{W-1}q_0(k) & -\rho^* & 0\cdots\cdots\cdots 0 & 0 & 0 \\ -q_0(0)\rho'_B & \rho^*+\rho'_B\sum_{k=0}^{W-2}q_1(k) & -\rho^*\cdots\cdots 0 & 0 & 0 \\ \vdots & & -\rho^* & 0 & 0 \\ q_0(w-3)\rho'_B & q_1(w-4)\rho'_B\cdots\cdots\cdots\cdots & \rho^*+\rho'_B\sum_{k=0}^{1}q_{w-2}(k) & -\rho^* & 0 \\ -q_0(w-2)\rho'_B & -q_1(w-4)\rho'_B\cdots\cdots\cdots\cdots & q_{w-2}(0)\rho'_B & \rho^*+q_{w-1}(0)\rho'_B & -\rho_A \end{bmatrix}$$

where $\rho^*=(1-\rho'_B)\rho_A$, and $\mathbf{B}=[1, 0, \cdots, 0]^t$

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[1] It is noted the inter-departure process of the link is equal to the arrival process of the station by Burke's theorem[7].

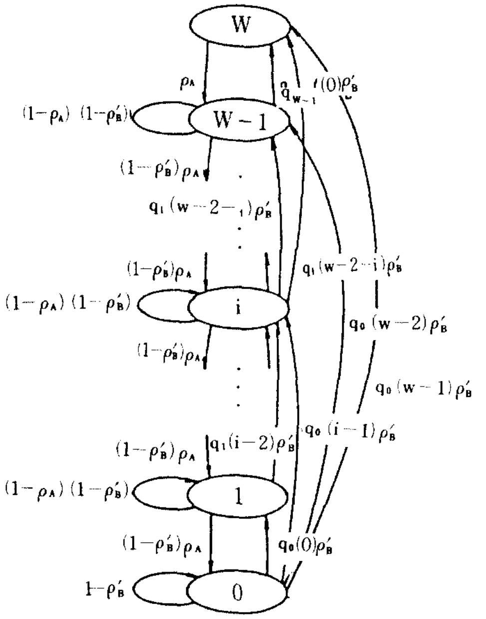

Fig. 4 A discrete-time Markov chain model of the send window process of the link layer.

D. Window Model of the Packet Layer

In this section, we consider the window mechanism of the packet layer. As mentioned previously, the packet layer has a sliding window protocol with the piggybacked acknowledgment scheme. A discrete-time Markov chain model of the receive window process is shown in Fig. 5. Here, ρ_{PA} and ρ_{PB} are the channel utilization of the information packet in the forward and reverse directions from the node A to B, respectively. Since the acknowledgment of the packet layer is generated only by the receive window process, the increase of the channel utilization due to the acknowledgment packet is negligible and therefore ignored. From the state-transition diagram of Fig. 5, there exists a solution satisfying the conservation law of flow. It may be shown that in the equilibrium state, the probability P_{pri} that the receive window width is in the i-th state is given by

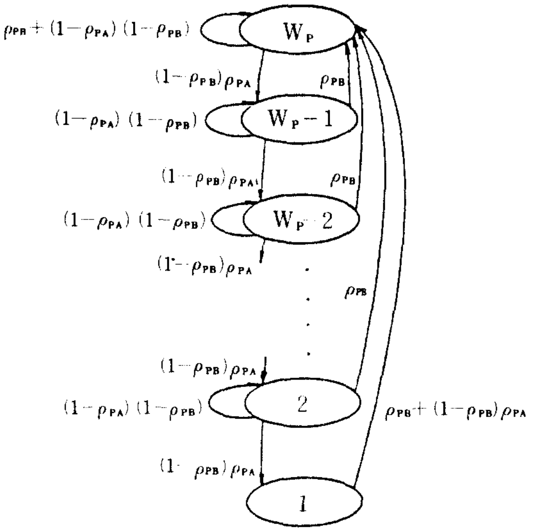

Fig. 5 A discrete-time Markov chain model of the receive window process of the packet layer.

$$P_{pri}=\frac{\dfrac{\rho_{PB}}{(1-\rho_{PB})\rho_{PA}}\left\{1+\dfrac{\rho_{PB}}{(1-\rho_{PB})\rho_{PA}}\right\}^{i-1}}{\left\{1+\dfrac{\rho_{PB}}{(1-\rho_{PB})\rho_{PA}}\right\}W_P-1}$$

$$1\leqq i\leqq W_P,\quad \rho_{PB}\neq 0$$

$$=\frac{1}{W_P},\quad 1\leqq 1\leqq W_P,\quad \rho_{PB}=0. \tag{16}$$

where W_p is the window size of the packet layer. The probability $\rho_{pr\phi}$ (see Section II-B) is given by

$$P_{pr\phi}=\frac{\dfrac{\rho_{PB}}{(1-\rho_{PB})\rho_{PA}+\rho_{PB}}}{\left\{1+\dfrac{\rho_{PB}}{(1-\rho_{PB})\rho_{PA}}\right\}W_P-1},\quad \rho_{PB}\neq 0$$

$$=\frac{1}{W_P},\quad \rho_{PB}=0 \tag{17}$$

A discrete-time Markov chain model of the send window process of the packet layer is shown in Fig. 6. One can see that the model is similar to that of the link layer. In this figure, $q_i'(k)$ is the probability that when the send window width is in the i-th state and the acknowledgment is received, the number of information packets correctly received at the other node is k+1, which is equal to the difference between the receive sequence number P(R) of acknowledgment and the last value of P(R) received. It is represented as

$$q_i'(k) = \int_0^\infty \binom{W_P - 1 - i}{k} (1 - e^{-\lambda_{PA} t})^k (e^{-\lambda_{PA} t})^{W_P - 1 - i - k} f_{P_r}'(t)\,dt \qquad (18)$$

where λ_{PA} is the inter-departure rate in the direction from the node A to B, and $f_{P_r}'(t)$ is the probability density of the residual life time at the node B. From the balanced flow equations of the send window process, the following equation is satisfied in equilibrium:

$$\mathbf{Q}' \mathbf{P}' = \mathbf{B}' \qquad (19)$$

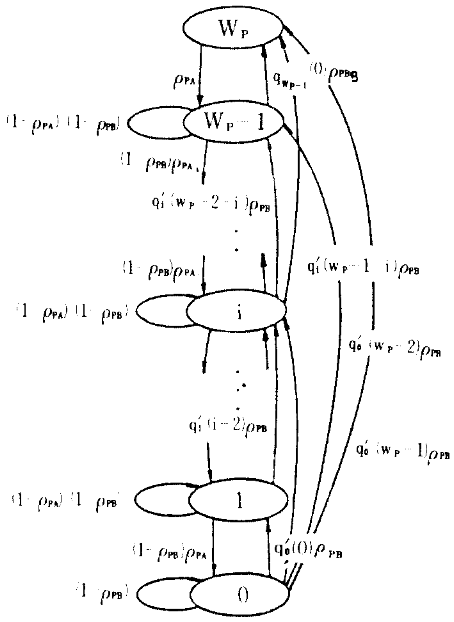

Fig. 6 A discrete-time Markov chain model of the send window process of the packet layer.

where $\mathbf{P}' = [P_{PS0}, P_{PS1}, \cdots, P_{PSW_P}]^t$, $\mathbf{Q}'$ is a $(W_P+1) \times (W_P+1)$ matrix represented by

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ \rho_{PB} \sum_{k=0}^{W_P-1} q_0'(k) & -\rho_P^* & 0 & 0 & 0 & 0 \\ -q_0'(0)\rho_{PB} & \rho_P^* + \rho_{PB} \sum_{k=0}^{W_P-2} q_1'(k) & -\rho_P^* & & 0 & 0 \\ & & & & \vdots & \vdots \\ \vdots & \vdots & & -\rho_P^* & 0 & 0 \\ -q_0'(W_P-3)\rho_{PB} & q_1'(W_P-4)\rho_{PB} & & \rho_P^* + \rho_{PB} \sum_{k=0}^{1} q'_{W_P-2}(k) & -\rho_P^* & 0 \\ -q_0'(W_P-2)\rho_{PB} & q_1'(W_P-3)\rho_{PB} & & -q_{W_P-2}(0)\rho_{PB} & \rho_P^* + \rho_{PB}\, q'_{W_P-1}(0) & -\rho_{PA} \end{bmatrix}$$

where $\rho_P^* = (1-\rho_{PB})\rho_{PA}$ and $\mathbf{B}' = [1, 0, \cdots, 0]^t$. (20)

III. THROUGHPUT AND DELAY ANALYSIS OF THE X.25 PROTOCOL

In the previous section, we have investigated the acknowledgment procedure and the window mechanism of the X.25. We now consider the following three performance measures at each layer; the normalized channel throughput which shows the effective transmission capacity due to the window protocol, the mean transmission time which indicates the time to send an information data correctly, and the transmission efficiency which reflects the packetization overhead and the burden of the flow control procedure.

A. Performance at the Link Layer

When the transmission capacity of the link layer is C_p bits/s, the effective link capacity C'_P is given by

$$C'_P = C_P(1 - P_{S\phi}). \tag{21}$$

That is, the effective link capacity is reduced by the probability that the transmission is suspended due to the window process. Also, the normalized link throughput T_L is represented by

$$T_L = 1 - P_{S\phi}. \tag{22}$$

Note that T_L reflects the effect of transmission blocking by the sliding window mechanism of the link layer.

To obtain the mean frame transmission time, we can use the concept of the virtual transmission time suggested by Bux et al.[3] For this performance measure, we perform the mean value analysis on the virtual transmission time. In doing so, we assume that the inter-departure process is Poisson, and that the data length is exponentially distributed.

The mean acknowledgment time $\bar{t}_{ack}$ between the end of the successful transmission of an information frame and the receipt of an acknowledgment is given by[6]

$$\bar{t}_{ack} = 2t_P + \bar{r} + p'_B \frac{E(\ell^2)}{2E(\ell)C'_P} + \rho'_B \bar{t}_I + (1 - \rho'_B)t_S \tag{23}$$

where t_p is the link processing time, $\bar{r}$ is the mean acknowledgment delay which is calculated from (2). $E(\ell)$ is the mean frame length, $\bar{t}_I$ is the mean transmission time of an information frame, and t_s is the transmission time of a supervisory frame. To determine the mean transmission time, we must distinguish between two cases in relation to window blocking. In one case, the acknowledgment time $\bar{t}_{ack}$ is greater than the time to transmit W-1 information frames (we denote T (W-1)). In this case, the effect of window blocking appears. In the other case, the time $\bar{t}_{ack}$ is not greater than T(W-1), and window blocking does not occur in the normal condition. Let T(n) be the time required for transmission of n information frames. Since the inter-departure time is assumed to be exponentially distributed, T(n) obeys the Erlangian distribution as[10]

$$f_{T(n)}(t) = \lambda_A e^{-\lambda_A t} \frac{(\lambda_A t)^{n-1}}{(n-1)!}, \tag{24}$$

and its mean is given by

$$E[T(n)] = \frac{n}{\lambda_A} \tag{25}$$

We now consider each of the two cases.

Case 1) $\bar{t}_{ack} > T(W-1)$

In this case, the mean frame transmission time $t_{\nu 1}$ is given by[3]

$$t_{\nu 1} = E[t_0] + P_B E[t_1] + \frac{P_B^2}{1 - P_B} t_2. \tag{26}$$

In (26) $E[t_o]$ is the mean transmission time of an information frame when the information frame considered is not disturbed, and is represented by the mean value analysis as

$$E[t_0] = \bar{t}_I + \bar{t}_d P_{S\phi} \tag{27}$$

where $\bar{t}_d$ is the mean delay time suffered from window blocking and is given by

$$\bar{t}_d = \bar{t}_{ack} - E[T(W-1)]. \tag{28}$$

Also, $E[t_1]$ in (26) is the mean time interval between the transmission of disturbed information frames and the first retransmission of this frame. It is obtained as

$$E[t_1] = \sum_{X=0}^{W-2} \{E[T(x+1)] + \sum_{i=0}^{X} \bar{t}_d P_{Si}\}$$

$$(1-P_B) P_B^X + P_B^{W-1} (t_{out} + t_s) + \bar{t}_{ack} + \bar{t}_I \quad (29)$$

where t_{out} is a time-out time, that is, the T_1 time of the X.25 protocol [1] . In addition, t_2 in (26) is the mean time interval between the retransmission time and the next retransmission time of this frame. It is given by

$$t_2 = t_{out} + t_s + \bar{t}_{ack} + \bar{t}_I . \quad (30)$$

Case 2) $\bar{t}_{ack} \leqq T(W-1)$

In this case, the effect of window blocking does not occur in a normal data transfer condition, but it occurs in erroneous situations. The mean transmission time $t_{\nu 2}$ in analogy to (26) is given by

$$t_{\nu 2} = \bar{t}_I + P_B E[t_1] + \frac{P_B^2}{1-P_B} t_2 \quad (31)$$

where $E[t_1]$ and t_2 may be obtained by the method of Bux et al. [3] and the method of mean value analysis.

With the results of cases (1) and (2), we can determine the mean frame transmission time t_ν . It is given by

$$t_\nu = t_{\nu 1} \cdot P[\bar{t}_{ack} > T(W-1)]$$

$$+ t_{\nu 2} \cdot P[\bar{t}_{ack} \leqq T(W-1)] \quad (32)$$

where

$$P[\bar{t}_{ack} > T(W-1)]$$

$$= 1 - e^{-\lambda_A \bar{t}_{ack}} \sum_{n=0}^{W-2} \frac{(\lambda_A \bar{t}_{ack})^n}{n!} \quad (33)$$

$$P[\bar{t}_{ack} \leqq T(W-1)]$$

$$= e^{-\lambda_A \bar{t}_{ack}} \sum_{n=0}^{W-2} \frac{(\lambda_A \bar{t}_{ack})^n}{n!} . \quad (34)$$

The transmission efficiency of the link layer may be determined by considering the total transmitted frame length ℓ_t for transmitting an information frame correctly. For the link layer data transmission, there are additional control frames and retransmitted information frames for flow control and error recovery. The same procedure with the analysis of the mean transmission time can be applied to the transmission efficiency. The transmission efficiency T_e of the link layer is given by

$$T_e = \ell_I / \ell_t \quad (35)$$

where ℓ_I is the length of an information frame.

B. Performance at the Packet layer

At the packet' layer, the normalized packet throughput T_p may be obtained by the same method as used for the link layer. It is given by

$$T_P = 1 - P_{PS\neq} . \quad (36)$$

That is, T_p is reduced by the probability $P_{PS\neq}$ due to the send window process.

Also, the mean transmission time $t_{P\nu}$ of an information packet is increased by the suspension time due to the window process. It is represented as

$$\bar{t}_{P\nu} = \bar{t}_{PI} + \bar{t}_{Pd} P_{PS\neq} \quad (37)$$

where $\bar{t}_{PI}$ is the mean transmission time of an information packet, $\bar{t}_{pd}$ is the mean delay time suffered from window blocking, which is given by

$$\bar{t}_{Pd} = \mathrm{Max}\{\bar{t}_{Pack} - E[t(W_P-1)], 0\} \quad (38)$$

where $\bar{t}_{pack}$ is the mean acknowledgment time and is calculated in the same way as for(23). Note that $E[t(W_p-1)]$ in (38) is the mean transmission time of W_p-1 information packets.

In addition, since the transmission efficiency Tpe of the packet layer is reduced by the packet header and the acknowledgment packet being generated, it may be expressed as

$$T_{Pe}=\frac{E\left[\ell_{Pi}\right]}{E\left[\ell_{P}\right]+\ell_{Ph}\cdot P_{Pr\phi}} \qquad (39)$$

where $E[\ell_P]$ is the mean packet length, $E[\ell_{Pi}]$ is the mean length of an information field, and ℓ_{Ph} is the packet header length (i.e., $E[\ell_P]=\ell_{ph}+E[\ell_{Pi}]$). It is noted that T_{pe} gives a measure of degradation of channel efficiency from the variations of packet length and probability that an acknowledgment is generated.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section we obtain and discuss the numerical results of the performance measures (i.e., normalized channel throughput, mean transmission time, and transmission efficiency) using the analysis results of Sections II and III. The numerical results are obtained under the conditions that the line speed is 64 kbps and the mean data length is about 1000 bits, and that the traffic has a Poisson process in a full-duplex channel. The simulation model considered is a network having two stations or models operated symmetrically under the X.25 protocol. Each station is represented by four process models; message-generate process, message-send process, message-receive process, and timer process. Each process functions individually with the queue-server system according to the X.25 protocol. The simulation results have been obtained using the SIMULA language.[11]

A. The Link Layer

In this subsection, the effects of link layer protocol parameters on the system performance are discussed. Here, the traffic model under consideration is assumed to be symmetric so that the forward and reverse channels are equally utilized.

Fig. 7 shows the normalized link throughput versus the link utilization with the link window

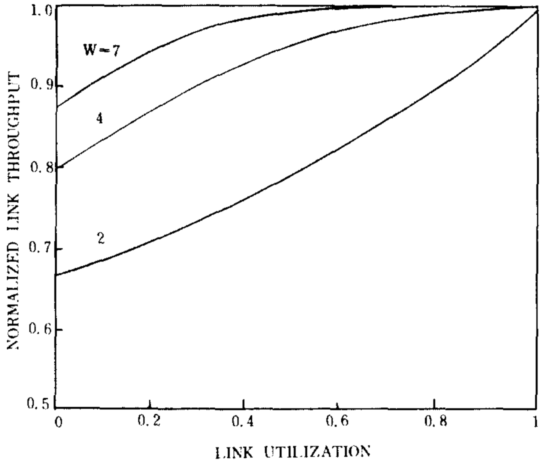

Fig. 7 Normalized link throughput versus link utilization for different window sizes. ($T_1=1$ s and $P_B=10^{-5}$)

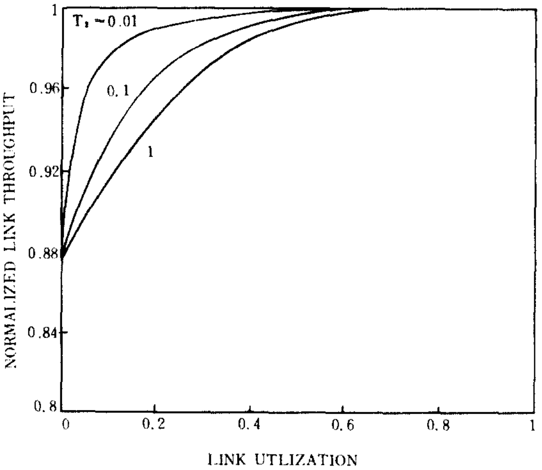

Fig. 8 Normalized link throughput versus link utilization for different values of T_1. ($W=7$ and $P_B=10^{-5}$)

size W as a parameter, and Fig. 8 shows the same with the acknowledgment delay T_2 as a parameter. In Fig. 7, the degradation effect of the effective link capacity is seen due to the window mechanism when the value of T_2 is 1 s which is rather large. As the channel utilization gets lower, the effective link capacity decreases because of window blocking, eventually becoming the same as the case of the fixed window mechanism. But, when the window size is relatively large, the impact of transmission blocking on the effective link capacity is negligible. In Fig. 8 which shows the effect of T_2 on the normalized link throughput, one can see that when the value of T_2 is nearly zero (at this value of T_2, the acknowledgment is immediately returned), the degradation of the throughput is rather negligible. However, when the value of T_2 is large, the effective link capacity reaches a lower bound of the window mechanism of the X.25 protocol.

The behavior of the mean frame transmission time for different values of T_2 is shown in Fig. 9. With the window size of 7, the mean frame transmission time is little affected by the variation of T_2. It is seen that even for the window size of 2, the increase of the mean frame transmission time is not very significant with the increase of T_2. It is also seen in this figure that the increase of T_2 makes the mean frame transmission time saturated to the upper bound which becomes the same as the case of the fixed window mechanism at low channel utilization.

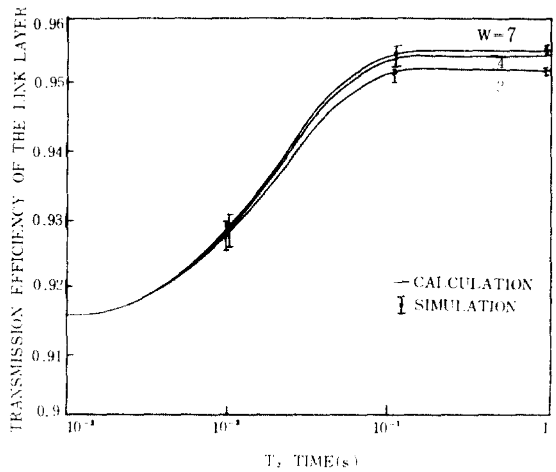

Fig. 10 Transmission efficiency of the link layer versus T_2 time for differnent window sizes. ($t_P = 50$ms, $\rho = 0.5$, $T_1 = 3$s, $P_B = 10^{-5}$, frame length = 1096 bits, and $C_P = 64$ kbps).

Fig. 10 shows the transmission efficiency of the link layer as a function of the T_2 value with the window size as a parameter. It is seen

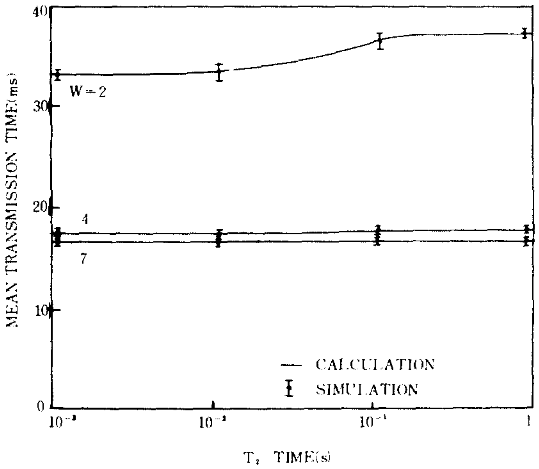

Fig. 9 Mean frame transmission time versus T_2 time for different window sizes. ($t_P = 50$ms, $\rho = 0.5$, $T_1 = 3$s, $P_B = 10^{-5}$, frame length = 1096 bits, and $C_P = 64$kbps).

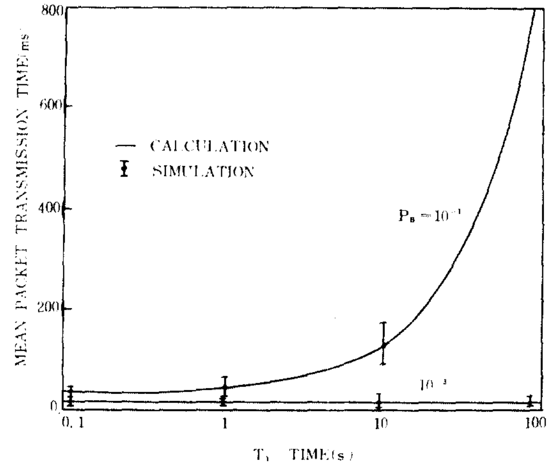

Fig. 11 Mean frame transmission time versus T_1 time for different channel error probabilities. ($T_2 = 0$ s, W = 7, frame length = 1096 bits, $C_P = 64$ kbps, and $t_P = 50$ms).

that the increase of T_2 improves the link efficiency by about 4%. This improvement results from the use of the piggybacked acknowledgment scheme using an information frame.

In Fig. 11, it is shown that the mean frame transmission time increases monotonically as the value of T_1 increases. Also, it is seen that when the channel error probability P_B is low, variation of T_1 has a negligible effect on the increase of mean transmission time. When the mean frame length is 1096 bits and the link capacity is 64 kbps, the variation of T_1 is less than 5 s, especially in a highly noisy channel. In general, the lower bound of T_1 is given by $2(t_P + t_l)$, where t_p is the nodal processing time and T_1 is the mean transmission time of an information frame (12), but at this value of T_1, transmission may become unstable in a noisy channel.

B. The Packet Layer

The normalized packet throughput versus packet utilization is shown in Fig. 12. One can see from this figure the degradation of the effective packet service capacity due to the windowing process. At the default window size of 2 recommended by the CCITT, the effective service capacity of the packet layer decreases by about 30% in the worst case as compared to the subscription service rate. Fig. 13 shows the mean transmission time of an information packet versus packet length for different window sizes. It is seen that the mean transmission time increases monotonically with the increase of packet length, and the effect of the window size on this performance is rather small. Fig. 14 shows the behavior of the transmission effeciency caused by the overhead

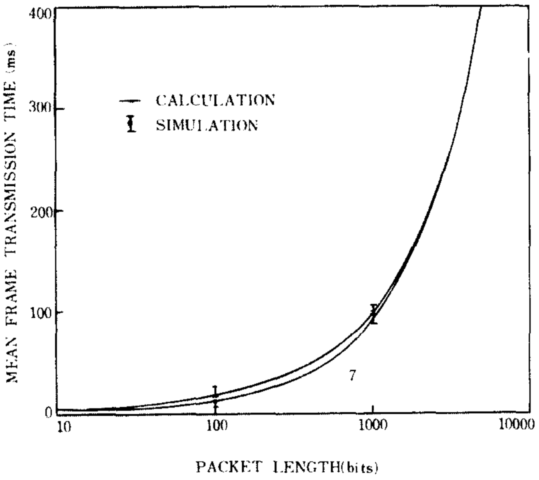

Fig. 13 Mean packet transmission time versus packet length for different window sizes. ($\rho_P = 0.7$, $c_P = 9600$ bps, and $t_P = 50$ ms)

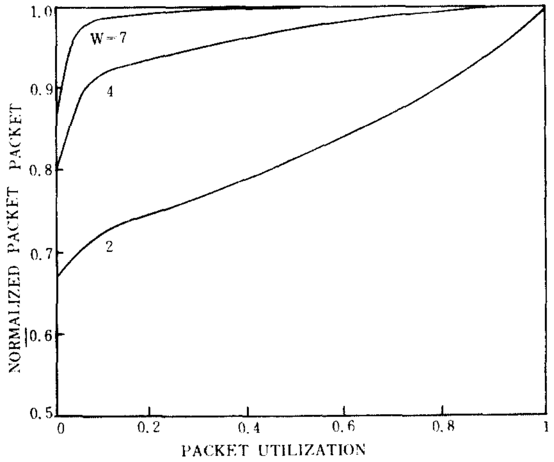

Fig. 12 Normalized packet throughput versus packet utilization for different window size. (packet length = 1024 bits, $C_P = 9600$bps).

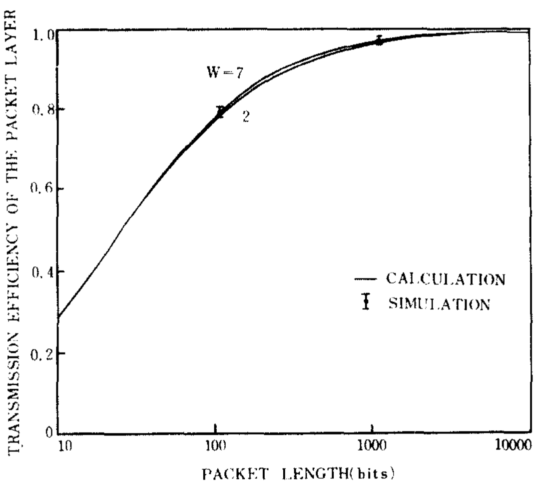

Fig. 14 Transmission efficiency of the packet layer versus the packet length for different window sizes. ($\rho_P = 0.7$, $c_P = 9600$ bps).

of the packetization and the window flow control. From Figs. 13 and 14, one can conclude that the effect of the window size on the mean transmission time and the transmission efficiency of the packet layer is negligible.

V. CONCLUSIONS

In this study, we have investigated the performance of the X.25 protocol and the selection of optimal protocol parameter values. To study the flow control mechanism of the X.25 protocol, we have used a discrete-time Markov chain model. This model can easily be applied for the analysis of various service environments, and it can also be used for the study of the protocol serving different types of data, such as voice, facsimile, video as well as data.

From the analysis of protocols of the two layers, we can make the following conclusions. In the link layer of the X.25 protocol, the window size must be greater than or equal to 7 to maintain the transmission capacity satisfactorily. The time duration of the acknowledgment delay timer, T_2, should be about 100 ms when the channel capacity is 64 kbps and the mean frame length is about 1000 bits, and the upper bound of T_2 must be determined in relation to the T_1 value. Nevertheless, the effect of T_2 is not critical (i.e., it results in only about 4% of variation in the transmission efficiency). Also, it has been found that the proper range of the time-out value, T_1, is in the order of 1 s. In a channel with low error rate, the variation of T_1 in this range has been found out to be not critical for the satisfactory performance.

In the packet layer of the X.25 protocol, it is desirable to have a window size that is greater than the default value to maintain the appropriate service rate at each virtual circuit. But, an increase of the window size requires an additional amount of nodal buffer storage. The packet length, which is an important parameter for the satisfactory performance of the packet layer, must be determined in relation to the performance of the link layer. It appears to be acceptable to have the default value recommended by the CCITT[1],[3], but in a channel with low error-rate it is desirable to have a larger value.

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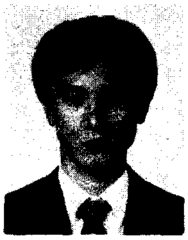

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