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Passive Star 토플로지와 WDM을 사용한 다중채널 광섬유 LAN을 위한 Multiple Access 프로토콜

(Multiple Access Protocols for a Multichannel Optical Fibre Local Area Network Using a Passive Star Topology and WDM)

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요 약

WDM으로 얻어지는 다중채널을 사용 LAN이나 MAN에서 사용자들을 passive star 토폴로지로 연결할 경우에 필요한 multiple access 프로토콜을 제안했다. 각 사용자가 한 개의 tunable 송신기와 한 개의 tunable 수신기를 갖고 있다고 가정하고 컨트롤 채널을 통해서 송수신기를 coordinate하는 방법을 모색했다. 제안한 방법은 최대 throughput가 송수신기간의 propation 시간, processing delay에 영향을 받지 않는 장점이 있다. 수치 예를 통해서 제안한 방법의 throughput과 기존의 방법들을 비교했다. 그리고 R-Aloha/Synchronous N-Server Switch 프로토콜의 경우에는 message 지연 시간을 분석했다.

Abstract

Two multiple access protocols are proposed for a multichannel WDM optical fibre local area network or metropolitan area network in which users are interconnected using a passive star topology. Each user has a single tunable transmitter and a single tunable receiver. A transmitter sends a control packet before its data packet transmission so that its intended receivers can tune to the proper data channel wavelength. The maximum throughput of the proposed protocols are independent of the effective normalized propagation delay which may include the transmitter and receiver tuning times and the processing delays. The maximum throughputs of the protocols are analyzed and compared with those of the existing ones by numerical examples. The message delay of the R-Aloha/synchronous N-server switch protocol which is suitable for the queued users is also analyzed.

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I. Introduction

With its enormous bandwidth, the optical fibre offers a high throughput channel for interconnecting users in a local area network (LAN) or in a metropolitan area network (MAN)[1]. Because of the simple connectivity in a bus or ring, as used in Ethernet, FDDI and DQDB, the bandwidth of the optical fibre cannot be fully utilized due to the throughput limit imposed by electro-optical conversion[2]. In spite of efforts in improving the existing multiple access protocols[3,4], the channel utilization of the interconnecting networks using a single channel is limited by the throughput of the electro-optical conversion.

Wavelength division multiplexing (WDM), which provides multiple parallel channels, has been conceived as a means of circumventing the throughput bottleneck of electro-optical conversion in a point-to-point connection[5].

In a LAN or MAN, where we need many-to-many connections, an additional problem of connectivity has to be solved in order to realize a high throughput network.

Among various network topologies, because of its capability to interconnect a relatively large number of users without requiring optical taps, optoelectronics repeaters and high capacity buffers[2], the passive star has emerged as one of the attractive topologies for an optical fibre LAN or MAN. In [6], a number of users are connected through a passive star coupler where each user has a single fixed wavelength transmitter and a tunable receiver. By making the receivers tune to the appropriate wavelength, high connectivity among the users can be achieved. However, the connectivity pattern should be pre-arranged and any change in traffic pattern should only be accommodated slowly by changing the connectivity pattern[7]. In order to rapidly change the connectivity, Chen et al.[8] have proposed the use of one additional transceiver with a fixed wavelength for control signal exchange. That is, a wavelength, say λ_0, is shared by all users for transferring control information needed for connectivity. Before transmitting its data over its dedicated wavelength, a transmitter sends control information in the control channel to inform its intended receiver so that the receiver tunes to the appropriate wavelength. In [9], the rapid connectivity is maintained without using an extra transceiver by making the transmitter, as well as the receiver, tunable.

The paper is organized as follows. Section 2 describes the system configuration and the access strategies under consideration. In section 3, we present and analyze the unslotted Aloha/polite access protocol. The R-Aloha/synchronous N-server switch protocol is presented and analyzed in Section 4. Numerical examples are given to compare the performance of the proposed protocols with that of other protocols in Section 5. The paper is concluded in Section 6.

II. System Description

In this paper, we consider the network configuration proposed by Habbab et al.[9] as shown in Fig. 1. There are $N+1$ channels, numbered 0 to N with wavelengths $\lambda_0, \cdots, \lambda_N$. One channel, say channel 0, called control channel, is used for transmitting control packets. The remaining channels, 1 to N, called data channels, are used for transmitting fixed size data packets. Each control packet contains a receiver address and possibly a data channel number ($\in \{1,2,\cdots,N\}$). A user has one tunable transmitter and one tunable receiver. An idle receiver, a receiver which is not receiving any data packet, continuously monitors the control channel for its address. Upon receiving a control packet containing its own address, the receiver tunes to the wavelength chosen by the control packet or determined by an algorithm commonly agreed on among the users. Besides allowing one to dynamically assign wavelengths for transmitter/receiver pairs, the availability of a separate control channel can be further exploited to implement priority (preemptive or non-preemptive) service for data packets, from a certain type of traffic. This feature would be particularly attractive for the system with multimedia traffic where different traffic types have different performance requirements. However, in this paper we will not concern ourselves with the priority service of data packets.

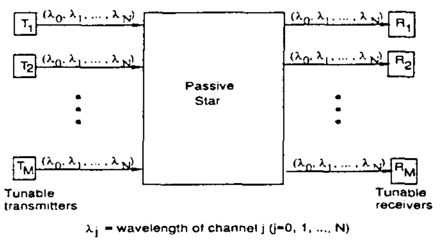

그림 1. Passive Star와 WDM을 사용한 다중채널 Optical LAN.
Fig. 1. Passive star multichannel WDM optical LAN

The transmission time of a data packet (called a data slot or simply a slot) is L times that of a control packet (called a control slot). We assume that L is an integer. We also assume that the normalized propagation delays, the propagation delay from one user to another in slots, are the same for all pairs of users, denoted by a[1]

1) If the transmitter and receiver tuning times are not negligible [14], they should be also included in a.

A multiple access protocol pair (P_c/ P_d) is needed for proper sharing of the control and data channels. P_c denotes the access protocol for the control channel and P_d denotes the access protocol for the data channels. Habbab et al.[9] have proposed a family of multiple access protocols for such a network. Others[10-13] have reported improvements to the access protocols in [9], which represent attempts to increase the throughput without unduly increasing the protocol complexity. A good survey of multiple access protocols for optical local area networks are given in [15]. According to the classification introduced in [15], our protocol belongs to the pretransmission coordination scheme.

Two multiple access protocols, slotted Aloha/polite access and slotted Aloha/synchronous N-server switch, which exhibit a larger asymptotic throughput values than the protocols described in [9-11, 13], were proposed in [12]. In this paper, we extend these multiple access protocols, for the multichannel LAN or MAN using a passive star topology, on the basis that the user has a single tunable transmitter and a single tunable receiver. The resultant protocols are referred to as unslotted Aloha/polite access and R-Aloha/synchronous N-server switch. The unslotted Aloha/polite access protocol is the unslotted version of the slotted Aloha/polite access. The unslotted Aloha/polite access protocol is simpler than the slotted Aloha/polite access protocol; yet, its maximum throughput rapidly converges to that of the slotted version as L increases (see Fig. 6). Its maximum throughput is analyzed and is shown to have the same asymptotic value as that of the more complex slotted version. The R-Aloha/synchronous N-server switch protocol, on the other hand, is a modification of the slotted Aloha/synchronous N-server switch protocol, where control information is transmitted using an implicit reservation access protocol. Once a user accesses a data channel successfully, it is allowed to access the data channel periodically until its data queue becomes empty, or a predetermined maximum holding time has been expired. This protocol attains a large maximum throughput even if L is rather small ($\approx N$) (see Fig. 7).

Similar reservation schemes have been proposed in [16-18]. The protocols in [16] and [17] are based on a system where two lasers (one fixed and one tunable) and two receivers (one fixed and one tunable) are available. Although the protocol proposed in [17] can be modified for a system with a single tunable laser and a single tunable receiver, the protocol assumes that there are the same number of data channels as the number of users. The reservation protocol proposed in this paper assumes a single tunable laser and a single tunable receiver. We also assume that there is a much larger number of users than the available number of data channels. The protocols in [18] can be implemented using a single tunable laser and a single tunable receiver and can accommodate a larger number of users than the number of data channels. However, it assumes that the feedback through the control channel is immediate, i.e., delayless. As the normalized propagation delay, a, increases the maximum throughput may significantly decrease. Also, the analysis of the reservation protocol, (R-ALOHA, Case 1), in [18] assumes that $L=N$. The proposed reservation protocol in this paper takes the propagation delay into account. As a result, unlike the carrier-sensing based protocols in [9,13] and the reservation based protocols in [11,18], which are sensitive to the propagation delay, the maximum achievable throughput of the proposed protocols are not propagation-delay sensitive. The throughput analysis of section 4.3 is valid for any $N(\geq L)$.

For the sake of simplicity, unlike in [8,11,15], the occurrence of receiver collisions, (the events that transmissions of two or more data packets destined to the same receiver overlap in time), is assumed negligible. However, with an increase in complexity, the proposed protocols can easily be modified to avoid receiver collisions.

Ⅲ. Unslotted Aloha/Polite Access Protocol

1. Protocol

A ready user, a user having a data packet to send, transmits a control packet in the control channel. Each control packet contains its intended receiver address and a data channel number chosen at random. If the control packet is successful and, further, if there is no other successful control packets having the same data channel number during one data slot prior to its own control packet transmission (called vulnerable slot), the user transmits its data packet over the chosen data channel immediately after the control packet is received.

Otherwise, (that is, the control packet collides or one or more successful control packets have the same data channel number as the one chosen by the user during its vulnerable slot), the user repeats the same procedure after a random delay. At each attempt, a data channel is chosen anew.

This protocol, like the slotted Aloha/polite access protocol[12], effectively eliminates data packet collisions by requiring a user to defer its data packet transmission whenever there is a possibility of a collision with another ス

data packet whose control packet was successfully transmitted earlier than its own control packet. However, it is necessary for a user to monitor the control channel during its vulnerable slot.

2. Throughput Analysis

We analyze the per-channel throughput, S_d, which is defined as the mean number of successful data packets per data slot per data channel. We make the following assumptions:

A1: Number of users in the network is infinite.

A2: The arrival process of control packets is Poisson with rate G per control slot. This means that we have a suitable retransmission control algorithm for avoiding instability in the control channel [19].

We use the following notations:

- G_{opt} = offered control channel traffic at which the maximum data channel traffic occurs.
- S_c= Pr [one control packet arrives during a control slot] = Ge^{-G}.
- $S_{c_{max}}$ = maximum of S_c.
- $S_{c_{opt}}$ = the value of S_c at which per-channel throughput is maximized.
- $S_{d_{max}}$ = maximum per-channel throughput.

The exact analysis of the unslotted Aloha/polite access protocol is given in Appendix A. Here, we will make the following assumption to simplify the analysis.

Assumption: Arrivals of successful control packets form a Poisson process with rate $S_c = Ge^{-2G}$ per control slot2.

2) The mean number of sucessful control packets is Ge^{-2G} per control slot because the unslotted Aloha is used in the control channel

This assumption allows one to obtain an explicit maximum per-channel throughput, $S_{d_{max}}$, which cannot be obtained using the exact analysis. As will be shown in the numerical examples, the maximum per-channel throughputs obtained using the approximate analysis are reasonably close to the exact results when $N>4$.

A successful control packet, called the tagged control packet, results in a successful data packet transmission if there is no other successful control packet that has the same data channel number as the tagged control packet within its vulnerable slot of length L control slots. Since the control packets successfully transmitted within the vulnerable slot start their transmission during the $L-1$ control slots (V2 as shown in Fig. A1), the per-channel throughput, S_d, is

$$S_d = \frac{L}{N} S_c e^{-(L-1)S_c/N}. \quad (1)$$

The maximum throughput is

for $L \geq 2Ne+1$,

$$S_{d_{max}} = \frac{L}{e(L-1)} \to \frac{1}{e} \text{ as} L\to\infty, \ S_{c_{opt}} = \frac{N}{(L-1)}; \quad (2)$$

for $L < 2Ne+1$,

$$S_{d_{max}} = \frac{L}{2Ne} e^{-(L-1)/(2Ne)}, \ S_{c_{opt}} = S_{c_{max}} = \frac{1}{2e}. \quad (3)$$

It is noted that the maximum throughput of the slotted Aloha/polite access for $L \geq Ne$, is [12]

$$S_{d_{max}} = \left(1-\frac{1}{L}\right)^{L-1} \to \frac{1}{e} \text{ as} L\to\infty, \ S_{c_{opt}} = \frac{N}{L}. \quad (4)$$

Ⅳ. R-Aloha/Synchronous N-Server Switch Protocol

1. Protocol

We will first describe the slotted Aloha/ Synchronous N-server switch protocol.

Slotted Aloha/Synchronous N-Server Switch Protocol [12]: The control channel time is divided into contiguous control slots: control slots are organized into frames of L control slots (one data slot). A ready user transmits its control packet in the first available control slot (Fig. 2). and examine all the control packets transmitted during the frame in which its control packet is transmitted (see Fig. 2). A control packet contains its intended receiver address but not a data channel number.

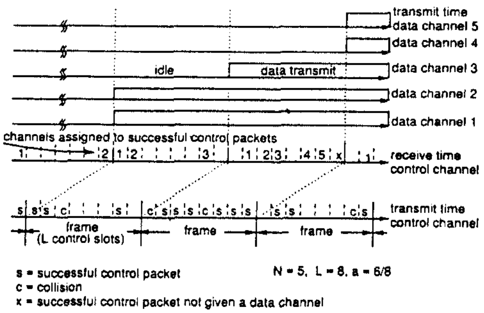

그림 2. Slotted Aloha/Synchronous N-server 스위치.
Fig. 2. Slotted Aloha/synchronous N-server switch.

When all the control packets of a frame are received, data channels are assigned to the successful control packets according to an assignment algorithm known to all the users in the network. For example, control packets may be given data channels on a FCFS basis starting from channel 1 to channel N as shown in Fig. 2[3]. If there are more successful control packets in a frame than the number of data channels, only N successful control packets are given data channels. Immediately after the assignment, the user successful in control packet transmission and successful in acquiring a data channel sends a data packet in the assigned data channel. The user which has a collided control packet or has a successful control packet, but was not given a data channel, repeats the same procedure after a random delay.

The maximum throughput of this protocol is considerably higher than that of other comparable protocols and is independent of the propagation delay [12]. However, in order to have a maximum throughput per data channel greater than 90 of the data channel capacity, the number of control slots per data slot L should be greater than about 3 × N. The following protocol that uses an implicit reservation protocol for the transmission of control packets and allows a user to seize a data channel periodically until its queue becomes empty or the maximum allowed channel holding time expires attains a high maximum throughput even if $L \approx N$.

An implicit reservation protocol, R-Aloha, was proposed for the satellite network in which a user, after acquiring a channel (a slot in a frame), is allowed to continuously use the channel until no more data is left in its queue [20]. The same protocol was applied for the transmission of packetized voice transmission over a ground radio channel [21]. In this subsection, we use the same idea in order to increase the maximum channel throughput of the WDM multichannel optical LAN where the throughput bottleneck occurs in the control channel. Because we have a multichannel network, an appropriate modification to the R-Aloha is needed.

Starting from the slotted Aloha/synchronous N-server switch, we further organize the frames (L control slots, or one data slot) into super-frames of length Q frames, where $Q \geq \lceil a+2 \rceil$ (see Fig. 3). We assume that $L \geq N$. The frames are partitioned into Q groups. The

3) Although not considered in the analysis, it is possible to eliminate receiver collisions using an appropriate assignment algorithm.

i^{th} frame is said to be a k-frame if $i=k$ mod Q ($k=0,1,\ldots,Q-1$). A user which is assigned a data channel, say channel j, in a k-frame will use the data channel in the subsequent k-frames until its data queue empties or the maximum allowed channel holding time elapses[4]. The user has an exclusive access right to the j^{th} control slots associated with the subsequent k-frames until the user releases data channel j. It is necessary for the user to indicate its intention to continue to use the channel (as indicated by $^{r}_{c}$ in Fig. 3) or to end using the channel (as indicated by $^{r}_{e}$ in Fig. 3) during the next k-frame. The unreserved control slots among the first N control slots and the remaining $L-N$ control slots are left for the transmission of control packets in a random access mode by the users currently not holding a data channel. Users successful in control packet transmission are given data channels using an algorithm agreed upon among the users.

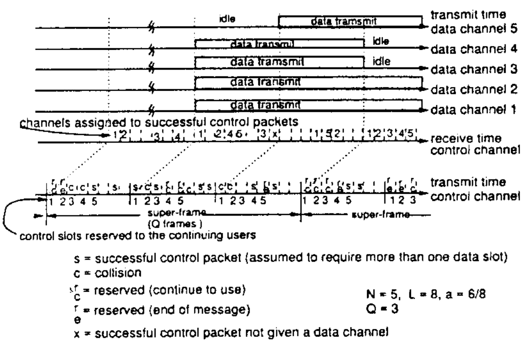

그림 3. R-Aloha/Synchronous N-server 스위치.
Fig. 3. R-Aloha/synchronous N-server switch.

A control packet contains its receiver address and flags for indicating whether the user has more than one data packet and whether it is a reserved transmission or a contention.

4) In the analysis, we assume that there is no limit on the maximum channel holding time.

2. Throughput Analysis

We will use the same assumptions (A1 and A2) and notations used in subsection 3.2. Because of assumption A2, groups in a super-frame are independent of each other. We, therefore, need to consider only one group. We analyze the maximum throughput with the following additional assumption..

A3: The probability that a user which has a channel access right releases a channel at the end of a frame is given by a constant, α.

Once a user acquires a channel, it will use the channel for the duration which is geometrically distributed with mean $1/\alpha$ (super-frames). This assumption will be exact if each user has a single message buffer and the message length is geometrically distributed and, will be a good approximation when the number of channels N is large.

Define Γ_n as the number of busy data channels during the n^{th} frame (slot) of a group. Owing to A3, the sequence $\Gamma_n, n\geq 1$ is a Markov chain whose transition probabilities are given by

$$P_{ij} \triangleq \Pr[\,\Gamma_{n+1}=j \mid \Gamma_n=i\,] \tag{5}$$
$$=\begin{cases} \sum_{k=0}^{i}\binom{i}{k}(1-\alpha)^k\alpha^{i-k}\binom{L-k}{j-k}(1-S_c)^{L-j}S_c^{j-k}, & j<N, \\ \sum_{k=0}^{i}\binom{i}{k}(1-\alpha)^k\alpha^{i-k}\sum_{m=N-k}^{L-k}\binom{L-k}{m}(1-S_c)^{L-k-m}S_c^{m}, & j=N \end{cases}$$

The steady state distribution of the number of busy channels is obtained by solving

$$\underline{\pi}=\underline{\pi}P, \text{ with } \underline{\pi}\,\underline{e}=1, \tag{6}$$

where $\underline{\pi} \triangleq (\pi_0,\pi_1,\pi_2,\ldots,\pi_N)$, $\pi_i \triangleq \lim_{n\to\infty}\Pr[\,\Gamma_n=i\,]$, $P \triangleq P_{ij}$ and $\underline{e} \triangleq (1,1,1,\ldots,1)^T$.

The per-channel throughput is given by

$$S_d = \frac{1}{N}\sum_{i=1}^{N} i\pi_i. \tag{7}$$

Because S_d is an increasing function of S_c, the maximum per-channel throughput is obtained by $S_{c_{opt}} = S_{c_{max}} = e^{-1}$.

3. Delay Analysis

The message delay is defined as the time between the arrival of a message and the end of the successful transmission of the message. In this section we analyze the mean message delay of the R-Aloha/synchronous N-server switch protocol under the following conditions.

1. There are M statistically independent and identical users each having an infinite size message buffer.
2. At each user messages arrive according to a Poisson process with rate Λ per data slot.
3. Denote message length, its first two moments and probability generating function by U, $\overline{U}$, $\overline{U^2}$ and $U(z)$, respectively.
4. When a message arrives at an empty queue during a frame, its control packet is transmitted in one of the available control slots (if there is any) during the next frame. If no data channel is allocated (due to a collision, or lack of available data channels or lack of control slots to transmit control packets), the control packet is retransmitted after a random delay.
5. In order to obtain the message delay, it is necessary to specify the actual retransmission algorithm. We will use the exponential back-off algorithm[5]. That is, the control packet is retransmitted during the R_i^{th} frame after i unsuccessful attempts to acquire a data channel, where R_i is geometrically distributed with mean $1/\gamma^i$. That is,

$$\Pr[R_i = j] = \gamma^i(1-\gamma^i)^{j-1},\ (0 < \gamma \le 1)\ j = 1, 2, 3, \cdots. \tag{8}$$

The first two moments of R_i are

$$\overline{R_i} = \frac{1}{\gamma^i},\ \overline{R_i^2} = \frac{2-\gamma^i}{\gamma^{2i}}. \tag{9}$$

In order to make the analysis tractable, we make the following approximations: 1) For a tagged user for which we obtain its message delay, the aggregate control packet arrivals from all users other than those from the tagged one is a Poisson process with rate G per control slot[6]. 2) The number of busy data channels seen by a control packet at the times of consecutive data channel acquisition attempts are independent of each other and distributed binomially with mean $\widetilde{S}_d$. That is,

$$\Pr\ [\textit{there are k idle data channels} \mid \textit{at the time of the } i^{th} \textit{ attempts}] = \binom{N}{k} \widetilde{S}_d^{\,k}(1-\widetilde{S}_d)^{N-k},\ k=0,1,2,\ldots,N, \tag{10}$$

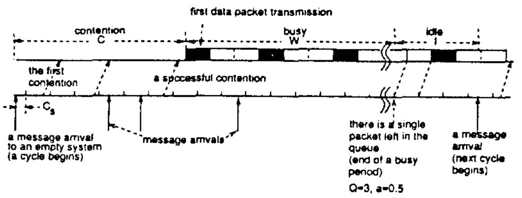

그림 4. 사용자의 contention, busy, idle 기간으로 구성된 한 개의 cycle

Fig. 4. A cycle of contention, busy and idle period of a user.

where $\widetilde{S}_d = S_d(\overline{W}+1+a)/(\overline{W}+1+a+Q)$, $S_d (\triangleq M\Lambda\overline{U}/N)$ is the data channel utilization and $\overline{W}$ is the mean busy period as shown in Fig. 4. A cycle consists of the contention, the busy and the

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5) The following analysis can be modified for other retransmission algorithms.

6) The use of G here is slightly different from that in Section 3. However, as $M \to \infty$, both definitions become identical.

idle periods. The contention period in turn consists of the initial synchornization period (C_s) and a number of slots during which a user attempts to gain the access to a data channel.

The two approximations require that the retransmission delays of control packets are sufficiently large [19]. Owing to these approximate assumptions, at each attempt, the probability that a user successfully acquires a data channel is given by a constant, say β. Therefore, the number of unsuccessful channel acquisition attempts a user makes before it acquires a data channel is geometrically distributed.

$$\Pr[\textit{a user acquires a data channel at the } (k+1)^{th} \textit{transmission attempt}] = \beta(1-\beta)^{k}, \quad k=0,1,2,\ldots \tag{11}$$

The analysis consists of the following steps.

0. Initialize G. For example, let $G=0$.
1. Obtain β.
2. Obtain the mean contention interval $\bar{C}$ (see Fig. 4).
3. Obtain the mean of the busy period $\bar{W}$ and the new estimate of G, G_{new}. If $|G_{new}-G|<\varepsilon$, do the next step. Otherwise repeat from step 1 with $G \leftarrow G_{new}$. Here ε is the pre-specified tolerance level.
4. Determine the mean message delay.

step 1: The probability of successfully acquiring a data channel, β, is given by

$$\beta = \sum_{k=0}^{N-1}\sum_{\xi=0}^{\infty}\left[\sum_{\nu=1}^{\min(\xi+1,\,L-k)} \min\left(1, \frac{N-k}{\nu}\right)\left(\frac{\nu}{\xi+1}\right)\phi(\nu|L-k, \xi+1)\right] \left[\frac{(LG)^{\xi}e^{-LG}}{\xi!}\right]\cdot\left[\binom{N}{k}\tilde{S}_{d}{}^{k}(1-\tilde{S}_{d})^{N-k}\right], \tag{12}$$

where $\phi(\nu|l,m)$ ($\triangleq$ Pr[there are ν control slots each containing a single control packet | m control packets are transmitted randomly in l control slots]) is given by [p. 112 of 22]

$$\phi(\nu|l,m) = \frac{(-1)^{\nu}l!\,m!}{\nu!\,l^{m}}\sum_{j=\nu}^{\min(l,m)}\frac{(-1)^{j}(l-j)^{m-j}}{(j-\nu)!\,(l-j)!\,(m-j)!} \tag{13}$$

The first term on the right hand side of equation (12) is the probability that the tagged user is successful in acquiring a data channel given that k data channels are in use and ξ other users attempt to acquire a data channel.

step 2: The contention interval in number of data slots, C, is divided into two components, C_f and C_v. C_f is independent of the number of data channel acquisition attempts and is given by

$$C_f = C_s + 1 + a, \tag{14}$$

where C_s is the initial frame synchronization time. Let X_i denote the interval from the time of a message arrival to the beginning of the next frame. Then

$$\begin{aligned} &\Pr[C_s \le x] \\ &= \sum_{l=1}^{\infty}\left(\prod_{i=1}^{l}\Pr[X_i \le x]\right)\Pr[l \text{ messages arrive} \in \text{one frame} \mid \text{at least one arrives}] \\ &= \sum_{l=1}^{\infty} x^{l}\frac{e^{-\Lambda}\Lambda^{l}}{l!(1-e^{-\Lambda})} = \frac{e^{-\Lambda}(e^{\Lambda x}-1)}{(1-e^{-\Lambda})}, \quad (0 \le x \le 1). \end{aligned} \tag{15}$$

The Laplace transform of the probability density function (pdf) of C_f is given by

$$C_f(s) = \frac{\Lambda e^{-\Lambda}e^{-(1+a)s}[1-e^{-(s-\Lambda)}]}{(1-e^{-\Lambda})(s-\Lambda)}. \tag{16}$$

C_v depends on the number of transmission attempts made before a data channel is assigned to the user. Denote C_{vk} as the variable component given that k ($k=0,1,2,\ldots$) retransmission attempts are made before a data channel is acquired by the user, then

$$C_{vk} = k\lceil a \rceil + \sum_{i=1}^{k} R_i. \tag{17}$$

The Laplace transform of the pdf of C_{vk} is

$$C_{vk}(s) = e^{-k\lceil a \rceil s} \prod_{i=1}^{k} \frac{\gamma^i e^{-s}}{1-(1-\gamma^i)e^{-s}}. \quad (18)$$

It follows that the Laplace transform of the pdf of C_v is

$$C_{v(s)} = \sum_{k=0}^{\infty} C_{vk}(s)\beta(1-\beta)^{k}. \quad (19)$$

and the Laplace transform of the pdf of C is

$$C(s) = C_{f(s)}, C_{v(s)}. \quad (20)$$

We will need the first two moments of C and $C(\Lambda)$. The first and the second moments of C_f are given by

$$\overline{C_f} = \overline{C_s} + 1 + a \quad (21)$$

$$\overline{C_f}^2 = \overline{C_s}^2 + 2(1+a)\overline{C_s} + (1+a)^2, \quad (22)$$

where

$$\overline{C_s} = \frac{\Lambda + e^{-\Lambda} - 1}{\Lambda(1-e^{-\Lambda})},$$

$$\overline{C_s}^2 = \frac{2+\Lambda^{2-2\Lambda-2}e^{-\Lambda}}{\Lambda^2(1-e^{-\Lambda})}.$$

The first two moments of C_{vk} are given by

$$\overline{C_{vk}} = k\lceil a \rceil + \sum_{i=1}^{k} \overline{R_i}, \quad (23)$$

$$\overline{C_{vk}^2} = k^2\lceil a \rceil^2 + 2\lceil a \rceil k \sum_{i=1}^{k} \overline{R_i} + \sum_{i=1}^{k} \overline{R_i^2} + 2\sum_{i=1}^{k} \sum_{j=i+1}^{k} \overline{R_i R_j}. \quad (24)$$

Using equations (9), (11), (23) and (24), we obtain the first and the second moments of C_v

$$\overline{C_v} = \sum_{k=1}^{\infty} \overline{C_{vk}} \beta(1-\beta)^k = \frac{(1-\beta)\{\lceil a \rceil(\gamma-1)+(1+\lceil a \rceil)\beta\}}{\beta(\beta+\gamma-1)} \quad (25)$$

$$\overline{C_v^2} = \sum_{k=1}^{\infty} \overline{C_{vk}^2}\beta(1-\beta)^k = \frac{\lceil a \rceil^2(1-\beta)(2-\beta)}{\beta^2} + \frac{2\lceil a \rceil(1-\beta)[\gamma-(1-\beta)^{2}]}{\beta(\beta+\gamma-1)^2} + \frac{(1-\beta)(2\gamma+1-\gamma^2-\beta)}{(\beta+\gamma-1)(\beta+\gamma^{2-1})}. \quad (26)$$

In order to have finite first two moments of C_v we need to satisfy $\gamma^2+\beta>1$. We then have the first two moments of C as

$$\overline{C} = \overline{C_f} + \overline{C_v}, \quad (27)$$

$$\overline{C^2} = \overline{C_f^2} + 2\overline{C_f}\,\overline{C_v} + \overline{C_v^2}. \quad (28)$$

We also have

$$C(\Lambda) = C_f(\Lambda), C_v(\Lambda), \quad (29)$$

where

$$C_f(\Lambda) = \left(\frac{\Lambda e^{-\Lambda}}{1-e^{-\Lambda}}\right) e^{-(1-a)\Lambda}, \quad (30)$$

and

$$C_v(\Lambda) = \sum_{k=0}^{\infty} e^{-k\lceil a \rceil}\beta(1-\beta)^k, \left[\prod_{i=1}^{k} \frac{\gamma^{ie^{-\Lambda}}}{1-(1-\gamma^i)e^{-\Lambda}}\right]. \quad (31)$$

step 3: The mean busy period, $\overline{W}$, is given by

$$\overline{W} = (\overline{\nu}-1), \overline{W_0} + \left(\frac{\overline{U}-1}{\overline{U}}\right)\overline{W_0} - (a-1), \quad (32)$$

where $\overline{\nu}$ is the mean number of messages in the queue just before the beginning of a busy period and $\overline{W_0}$ is the contribution to the mean busy period by a single message which was in the queue just before the beginning of a busy period. The second and the third terms of equation (32) are due to that the busy period ends when the queue has only one packet in the queue at the time of control packet transmission (see Fig. 4). We have [23]

$$\overline{W_0} = \frac{\overline{UQ}}{1-\Lambda\overline{UQ}}, \quad (33)$$

and

$$\overline{\nu} = \Lambda\overline{C} + 1. \quad (34)$$

The message arrival times at an empty queue is a renewal process. The mean interval between successive renewal times, $\overline{\tau}$, is given by begin{equation}

$$\overline{\tau} = \overline{C} + \overline{V} + 1/\Lambda. \quad (35)$$

Owing to the renewal-reward theorem [24], the rate of request transmission generated by a single user is given by $1/(\beta\bar{\tau})$ per frame. Therefore, G, is obtained by

$$G=\frac{M-1}{\beta\bar{\tau}L}. \quad (36)$$

step 4: The mean message delay is obtained using a generalized M/G/1 model. Denote B_0, B_1 and B as the service time of the message that initiates a busy period, the service time of the message that arrives at the queue when the last message is being transmitted and the service time of the message that arrives at the queue when there are at least two messages in the system (at least one message in the queue and one being transmitted), respectively. Also denote $B_{0(s)}, B_{1(s)}$ and $B(s)$ as the Laplace transforms of the pdf of these service times. Then, the mean message delay, $\bar{D}$, is

$$\bar{D}=\frac{V''(1)+y_1\{2[V_1'(1)-V'(1)]+[V_1''(1)-V''(1)]\}+y_0[2V'(1)+V_0''(1)-V''(1)]}{2\Lambda[1-V'(1)]}-(Q-1). \quad (37)$$

where

$$V_i(z)=B_i(\Lambda-\Lambda z),(i=0,1 \text{ or no }_{\text{script}}), \quad (38)$$

$$y_0=\frac{[1-V'(1)]V_{1(0)}}{[1-V_{0(0)}][V_{1(1)}-V'(1)]+V_{1(0)}[1+V_{0(1)}-V'(1)]}, \quad (39)$$

$$y_1=y_0\frac{1-V_{0(0)}}{V_{1(0)}}, \quad (40)$$

$$B(s)=U(e^{-sQ}), \quad (41)$$

$$B_0=B(s)C(s), \quad (42)$$

$$B_{1(s)}=p_0B_0(s)+(1-p_0)B(s), \quad (43)$$

$$p_0=\Pr[U=1]+[e^{\Lambda(Q-1+a)}-1]\sum_{l=2}^{\infty}\frac{e^{-\Lambda lQ}\Pr[U=l]}{1-e^{-\Lambda lQ}}. \quad (44)$$

The prime denotes derivatives with respect to z and the last term of equation (37) is due to the fact that actual transmission time of a packet is one data slot. The derivation of equation (37) is in Appendix B.

V. Numerical Examples

We will first compare the maximum throughputs obtained using the approximate analysis for the unslotted Aloha/polite access with the exact results. The maximum throughputs obtained using the approximate analysis for $N=2,3,5$ and 10 are shown in Fig. 5. In the same figure the exact results are also shown. The approximate results agree reasonably well with the exact ones for $N\geq5$. For $N=2$ and $N=3$, however, the approximation tends to overestimate the maximum throughput. The error reaches the maximum at $L\approx2Ne$. As mentioned in Section 3, the exact analysis does not provide an explicit formula for the maximum throughput, $S_{d_{max}}$. Because numerical integrations are needed to evaluate the functions in equations (A2-A4) of Appendix A, it is time consuming to obtain the maximum throughput using the exact analysis.

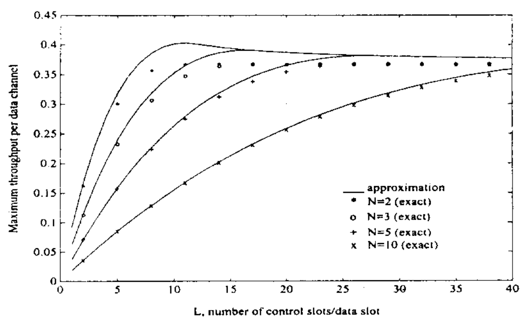

그림 5. Unslotted Aloha/Polite Access 프로토콜의 근사분석과 정확한 분석의 비교

Fig. 5. Comparison of exact and approximate analysis of the unslotted Aloha/polite access.

The maximum per-channel throughputs of the original [9] and improved [10] (un)slotted Aloha/Aloha and (un)slotted

Aloha/polite access protocols are compared for $N=5$ in Fig. 6. The slotted versions have significantly larger maximum throughput than the corresponding unslotted versions for L less than about two to three times the number of channels, N. As the number of control slots per data slot, L, increases the difference in throughput between the slotted and the unslotted versions decreases and the throughputs converge to their respective asymptotic values ($1/e$ or $1/2e$ depending on the protocol).

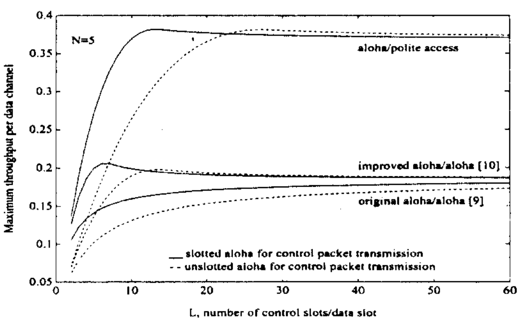

그림 6. Aloha/Aloha와 Aloha/Polite Acess 프로토콜의 비교

Fig. 6. Comparison of the Aloha/Aloha and Aloha/polite access protocols.

The increase in the throughputs using the improved versions[7] proposed by Mehravari [10] is significant for relatively small values of L. For example, the maximum throughput of the improved unslotted Aloha/Aloha protocol is about 1.5 times that of the original unslotted Aloha/Aloha protocol for $L=10$. However, as L increases, the throughput difference between the improved versions and the original versions becomes negligible.

Polite access schemes (slotted or unslotted versions) have much larger maximum throughput compared with other protocols except for very small values of L ($L<N$).

Similar observations can be made with $N=10$ (see Fig. 11) with an appropriate Similar observations are made with other values of N with an appropriate scaling of L.

The performance of a reservation based protocol improves as the message length increases. The maximum throughputs of the R-Aloha/synchronous N-server switch protocol are shown in Fig. 7 for $N=5$ and $L=5,7,9$ and 11. As expected, as the mean time a user holds a channel (in number of super-frames), or the mean number of data packets that a user transmits once the user acquires a channel, increases, the maximum throughput of the protocol increases. It is noted that the maximum per-channel throughput of greater than 0.9 is achieved when the mean number of packets transmitted consecutively by a user is greater than 16 even for $L=N$ in this example. It is also noted that the incremental increase in the maximum throughput as L increases is small when the mean holding time is greater than 10 and $L>N$.

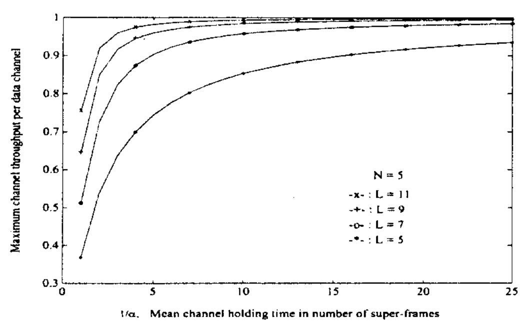

그림 7. 평균 holding time 대 R-Aloha/ Synchronous N-Server 스위치의 throughput

Fig. 7. Maximum per-channel throughput versus mean channel holding time of the R-Aloha/synchronous N-server switch.

In Figs. 8-10, we plot the mean message

7) The maximum throughput of the improved unslotted Aloha/Aloha protocol is obtained using the same assumption as the one used in the approximate analysis of the unslotted Aloha/polite access protocol.

delay and the mean contention period of the R-Aloha/synchronous N-server switch protocol with $N=5, a=0.5, Q=3$ and $\overline{U}=2$.

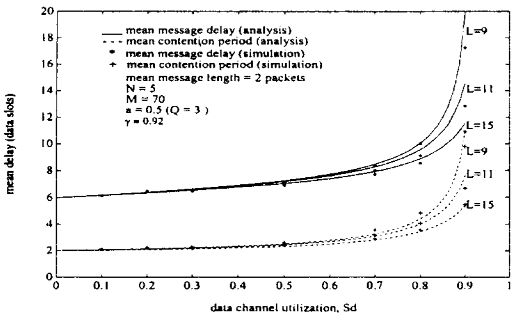

그림 8. R-Aloha/Synchrouous N-Server 스위치의 평균 메시지 delay와 contenting period.

Fig. 8. Mean message delay and mean contention period versus data channel utilization of the R-Aloha/synchronous N-server switch.

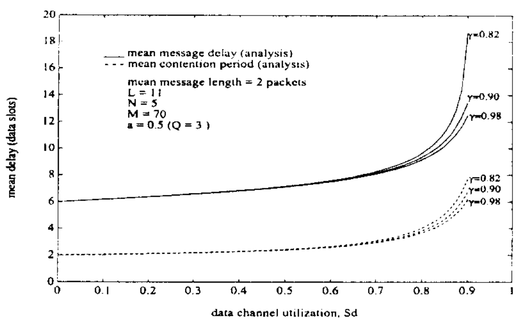

그림 9. R-Aloha/Synchrouous N-Server 스위치의 평균 메시지 delay와 contenting period.

Fig. 9. Mean message delay and mean contemtion period versus data channel utilization of the R-Aloha/synchronous N-server switch.

The message length is assumed to be geometrically distributed in these examples. The effect of increasing L, the number of control slots per data slot, is examined in Fig. 8 ($M=70, \gamma=0.92$). As expected, the mean message delay decreases as L increases. The decrease, however, is rather small unless the data channel utilization, S_d, is large ($S_d>0.85$) and $L<11$. On the same figure, simulation results are also shown for comparison.

In Fig. 9, we vary the retransmission parameter γ with L and M fixed at 11 and 70, respectively. It is seen in this example, the change in delay is not significant as γ is varied from 0.82 to 0.90 and then to 0.98.

In Fig. 10, we keep $\gamma=0.82$ and $L=11$ and vary the user population M from 30 to 100. The increase of M from 30 to 100 causes a very small increase in the mean contention period. However, the mean message delay decreases considerably due to the decrease in message queueing delay at user queues.

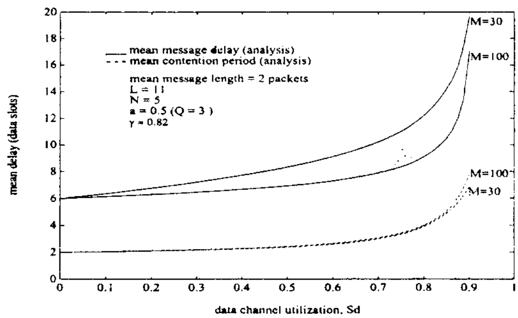

그림 10. R-Aloha/Synchrouous N-Server 스위치의 평균 메시지 delay와 contenting period.

Fig. 10. Mean message delay and mean contention period versus data channel utilization of the R-Aloha/synchronous N-server switch.

Ⅵ. Conclusions

In this paper, we have proposed two multiple access protocols for a multichannel WDM optical fibre local area network or metropolitan area network. Users are connected using a passive star optical fibre. Each user has a single tunable transmitter and a single tunable receiver. The comparisons of the maximum throughput of the proposed protocols with that of the existing ones show that the proposed protocols achieve higher throughput than the similar existing protocols over a wide range of parameter values such as L and N. The maximum throughput of the proposed protocols are independent of the effective normalized propagation delay, a, which must take tuning times and processing delays into account.

Depending on the network environment, a suitable protocol may be chosen from among the existing protocols and the protocols proposed in this paper. For example, when protocol complexity is the main concern and the data slot size is much larger than the control slot size ($L \gg N$), the unslotted Aloha/polite access may be a reasonable choice. The protocol is simple and yet has a relatively high asymptotic (in L) maximum per-channel throughput of $1/e$. On the other hand, if L cannot be made much larger than N and the periodic channel access by the users is desirable, the R-Aloha/synchronous N-server switch protocol can be used for a very high throughput network with an added protocol complexity.

APPENDICES

A. Exact Analysis of the Unslotted Aloha/ Polite Access

Problem statement: Given that a control packet (called tagged packet) arrives, determine the probability that the corresponding data packet is successfully transmitted.

Two conditions need to be satisfied.

C1: No other control packet arrives during vulnerable period V1 as indicated in Fig. A1.

C2: No other control packet having the same data channel number as the tagged packet arrives during vulnerable period V2. This is equivalent to the event that no other control packet having the same data channel number as the tagged packet ends its transmission within the period V2′.

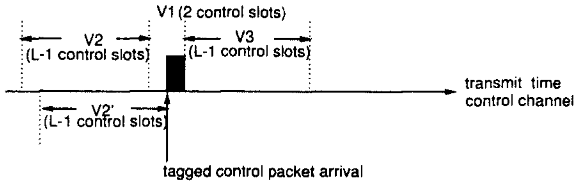

그림 A1. Improved Unsloted Aloha/Aloha와 unslotted Aloha/Polited acess의 vulnerable poriod.

Fig. A1. Vulnerable periods of the improved unslotted Aloha/Aloha and unslotted Aloha/polite access protocols

Per-channel throughput is then given by

$$S_d = \frac{GL}{N} \cdot \Pr[C1] \cdot \Pr[C2|C1],$$

where $\Pr[C1] = e^{-2G}$. Suppose that the tagged control packet is of class i, that is, its data channel number is i. To obtain $\Pr[C2 \mid C1]$, we define $T \triangleq$ time at which the nearest (in the past) a successful transmission of a control packet of class i ends. Then $\Pr[C2 \mid C1] = \Pr[T \geq L-1]$. Define $F(t) \triangleq \Pr[T \leq t]$.

For $0 \leq t \leq 1$: Suppose that the nearest class i control packet ended its transmission at x (see Fig. A2(a)). The control packet will be successful if it does not experience either of two types of collisions.

1. collision with another control packet arriving before the control packet (type 1 collision)
2. collision with another control packet arriving after the control packet (type 2

collision)-- Because the control packet is the nearest (in reverse time) control packet of class i from the tagged control packet, there is no other control packet of class i arriving within $\min(x,1)$ control slots.

We have

$$F(t) = \int_0^t \frac{G}{N} e^{-Gx/N} \cdot e^{-G} \cdot e^{-G(1-1/N)x} dx = \frac{1}{N} e^{-G}(1-e^{-Gt}). \quad (A1)$$

For $t>1$: Given that the first control packet of class i ends its transmission at x, there are three mutually exclusive events (see Fig. A2):

1. The first arrival of class i in reverse time (the last packet before the tagged packet) is successful.
2. Type 2 collision occurs but type 1 collision does not.
3. Type 1 collision occurs.

The probability distribution of T conditioned on that one of the above occurs follows:

$$F_{1(t)} \triangleq \Pr[\, T<t \mid \text{the first event occurs}] = \int_0^t \frac{G}{N} e^{-Gx/N} \cdot e^{-G} \cdot e^{-G(1-1/N)\cdot \min(x,1)} dx, \quad (A2)$$

$$F_{2(t)} \triangleq \Pr[\, T<t \mid \text{the second event occurs}] = \int_0^t \frac{G}{N} e^{-Gx/N} \cdot e^{-G} \cdot (1-e^{-G(1-1/N)\cdot\min(x,1)}) \cdot F(t-x-1)dx, \quad (A3)$$

$$F_{3(t)} \triangleq \Pr[\, T<t \mid \text{the third event occurs}] = \int_0^t \frac{G}{N} e^{-Gx/N} \cdot (1-e^{-G}) \cdot \left(\int_1^{t-x} \psi(u)F(t-x-u)du\right)dx, \quad (A4)$$

where $\psi(u)$ is the probability density function of the cluster length given that type 1 collision occurs (see Fig. A2(c)). The cluster length measured from the time class i control packet transmission ends is one control slot when only type 2 collision occurs. Hall [25] gives the density function $\psi(u)$ as

$$\psi(u) = \begin{cases} \frac{G}{e^G-1}\Big[\, 1+\sum_{j=1}^{\lfloor u-1 \rfloor} \frac{(-1)^j e^{-jG}}{j!} (G^j(u-j-1)^j + jG^{j-1} (u-j-1)^{j-1})\Big], & u \ge 1 \\ 0, & u \ge 1 \end{cases} \quad (45)$$

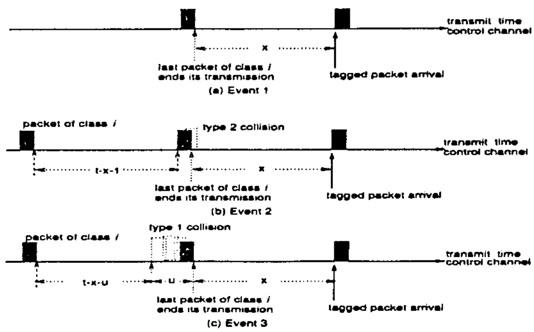

그림 A2. F(L)을 계산하기 위한 세 개의 Event
Fig. A2. Three mutually exclusive events for computing F(t)

where $\lfloor \cdot \rfloor$ is the largest integer not greater than the argument. We then have

$$F(t) = F_1(t) + F_2(t) + F_3(t) \quad (A6)$$

$$\Pr[C2|C1] = 1 - F(L-1). \quad (A7)$$

Algorithm for computing $F(t)$:

1. Using equation (A1), obtain $F(t)$ for $0 \le t \le 1$.
2. Using equations (A2~A6) and $F(t-1)$, obtain $F(t)$ for $1 < t \le 2$.
3. Repeat 2 after increasing the range of t by 1 until $L-2 < t \le L-1$.

B. Derivation of Equation(37)

Denote Y_n as the number of messages left behind at the time of the n^{th} message departure. Also denote V, V_1 and V_0 as the number of messages arriving during the transmission time of a message which arrives while there are more than one message, exactly one message and no message in the system, respectively. The messages in the system include the messages in the queue of the tagged user and the message from the tagged user which is being transmitted. Then we have

$$Y_{n+1}=\begin{cases} Y_{n-1+V}, & \text{for } Y_n\geq 2,\\ V_1, & \text{for } Y_n=1,\\ V_0, & \text{for } Y_n=0.\end{cases} \quad (A8)$$

Assuming that Y_n has a steady state distribution, its generating function $\lim_{n\to\infty}\sum_{k=0}^{\infty} z^k \cdot \Pr[Y_n=k]$, $Y(z)$, is

$$Y(z)=\frac{y_1 z[V_{1(z)}-V(z)]+y_0[zV_{0(z)}-V(z)]}{z-V(z)}, \quad (A9)$$

where $y_i \triangleq \lim_{n\to\infty} \Pr[Y_{n}=i]$ $(i=0,1)$ and $V(z)$, $V_{0(z)}$ and $V_{1(z)}$ are the generating functions of V, V_0 and V_1, respectively. Using that $Y(1)=1$ and $Y'(0)=y_1$, we obtain

$$y_0=\frac{[1-V'(1)]\;V_{1(0)}}{[1-V_{0(0)}][V_1'(1)-V'(1)]+V_1(0)[1+V_0'(1)-V'(1)]},$$
$$y_1=y_0\frac{1-V_0(0)}{V_1(0)}.$$

Since the message arrival is a Poisson process with rate Λ, we have [23]

$$V_{i(z)}=B_i(\Lambda-\Lambda z), (i=0,1, \text{ or no subscript}),$$

where

$$B(s)=\sum_{l=1}^{\infty} e^{-sQl}\cdot \Pr[U=l]=U(e^{-sQ}) \text{ and } B_0(s)=B(s)C(s). \quad (A10)$$

The transmission time of the message that arrives while the last message in the system is being transmitted is given by

$$B_1=\begin{cases} B_0, & \text{if \textit{the message arrives when the remaining service time is less than} } Q+1+a,\\ B, & \textit{otherwise.}\end{cases} \quad (A11)$$

Denoting p_0 as the Pr [the message arrives when the remaining service time is less than $Q+1+a$], we have

$$B_1(s)=p_0B_0(s)+(1-p_0)B(s). \quad (A12)$$

We note that $p_0=1$ if the length of the message being served is 1. When the message length is $l(\geq 2)$, we have

$$p_0=\sum_{k=1}^{\infty}\frac{e^{-\Lambda lQ}(\Lambda lQ)^k}{k!(1-e^{-\Lambda lQ})}\cdot\left(\frac{Q+1+a}{lQ}\right)^k, \text{ if } U=l. \quad (A13)$$

The first term in the summation of equation (A13) is the probability that k messages arrive during the transmission of a message conditioned on that at least one message arrives, and the second term is the probability that all the messages arrive during the last $(Q+1+a)$ slots of service time of the message being served. Therefore, we have

$$p_0=\Pr[U=1]+[e^{\Lambda(Q+1+a)}-1]\sum_{l=2}^{\infty}\frac{e^{-\Lambda lQ}\Pr[U=l]}{1-e^{-\Lambda lQ}}. \quad (A14)$$

Using the Little's result [23] and that the actual packet transmission time is one data slot, we have

$$\overline{D}=\frac{Y'(1)}{\Lambda}-(Q-1), \quad (A15)$$

which reduces to equation (37) in the text.

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