# Analysis of mean packet delay in DR-MPCP limited service using queueing theory

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***Abstract*—Ethernet passive optical access network (EPONs) have become widespread optical access network. In EPON uplink communication, communication is reserved by polling from an optical network unit (ONU) to an optical line terminal (OLT) using multi-point control protocol (MPCP). A method of delaying the transmission timing of REPORT messages in MPCP, called delayed REPORT messages-MPCP (DR-MPCP) has been proposed as a way of reducing the mean packet delay time of EPON uplink communication [1][2]. However, this method cannot limit the transmission window size of each ONU (making it gated service). In real networks, the transmission window size should be limited to be fair to each ONU (i.e. it should be limited service). This paper derives the upper limit and theoretical expression of the mean packet delay time in DR-MPCP limited service using the queueing theory M/G/1 model. It also analyzes the characteristics of mean packet delay.**

***Keywords*—*Ethernet Passive Optical Network (EPON), MPCP, DR-MPCP, M/G/1-model, Mean packet delay.***

## I. INTRODUCTION

Access networks connect subscribers such as business offices or house with a service provider's station, which connects to a metropolitan area network or wide area network. Recently, fiber to the home (FTTH) is widely used among access networks. A passive optical networks (PON) is one technology that support FTTH. PONs connect an optical splitter to an optical fiber to which an optical line terminal (OLT) is connected, branches the optical signal, and broadcasts to optical network unit (ONU). Among PON technologies, Ethernet passive optical networks (EPONs) are one of the most popular methods at present [3]. However, EPON has a problem: the mean waiting time of arriving packets (mean packet delay) is long. Thus, the mean packet delay must be decreased to create more efficient access networks. In downlink communication, i.e. packet transmission from the OLT to the ONU, a packet is broadcast through the optical splitter, so the delay of each packet does not significantly affect communication quality. However, in an EPON uplink, i.e. the communication from the ONU to the OLT, time division multiple access (TDMA) is used. This requires dynamic bandwidth allocation (DBA) to appropriately scheduling data to avoid packet collisions. With DBA, each ONU sends its transmission request to an OLT, and then each ONU can reserve the network resources through a reply from the OLT.

The exchange of messages for this reservation is defined by the multipoint control protocol (MPCP) media access method [4]. In MPCP, each ONU sends its set of the transmission requests to the OLT as a 64-byte REPORT message. The OLT calculates both the transmission window and transmission starting time for each ONU. The transmission window is the data size, which means that an ONU can transmit only a reserved amount of packets in each cycle. The OLT sends the calculation result as a GATE message. Then, the ONU sends the packets. Thus, the communication time in the uplink is divided into a reservation interval for the packet transmission control and a data interval for the packet transmission itself.

In EPONs with MPCP, interleaved polling with adaptive cycle time (IPACT) is a common polling method [5]. However, there is a problem with the IPACT method. For this reason, Miyata et al. proposed advanced MPCP called delayed REPORT messages-MPCP (DR-MPCP), in which the transmission timing of the REPORT message is delayed [1][2]. They also modeled DR-MPCP and derived its mean packet delay using the M/G/1 queueing model. They found that the mean packet delay of DR-MPCP is shorter than that of IPACT. However, in [1][2], they analyzed only gated service despite limited service being used in real networks.

Therefore, we analyzed the theoretical expression and characteristics of mean packet delay in limited service using M/G/1 queueing model. To analyze limited service, we first extended the analysis that converts gated service to limited service [1][2]. Using the analysis, we analyzed the upper bound of the mean packet delay of DR-MPCP limited service. After that, we derived an exact solution for the mean packet delay of DR-MPCP limited service while considering round trip time (RTT) for reservation and showed the effectiveness of DR-MPCP using numerical calculation and a simulation.

## II. CLASSIFICATION OF SYSTEM MODEL

The basis of the queueing theory analysis used in this research is the polling system [6]. In the polling system, illustrated in Fig. 1, N users send packets in order. The number in this figure means the number of the data interval and reservation interval of the ONU. The total interval obtained by combining the reservation and data intervals of N users is called a cycle. The packets that arrive within a cycle are reserved to be transmitted simultaneously in one reservation interval. There are three systems for determining which packets

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are transmitted during the data interval of each cycle: a gated system, an exhaustive system, and a partially gated system [6]. In a gated system, packets that arrive before the reservation interval are transmitted in the data interval. In an exhaustive system, packets that arrive in the reservation and data intervals are all transmitted in the data interval. In a partially gated system, packets that arrive before the data interval are transmitted in the data interval, even if they arrive after the reservation interval. In gated service, all requested packets in a cycle are transmitted within their own data interval. In contrast, in limited service, the amount of transmittable packets is limited (pre-determined) for each data interval.

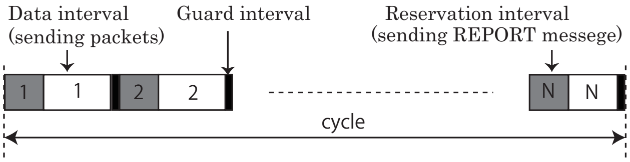

Fig. 1. Polling system.

Table I and II show the differences between IPACT [5] and DR-MPCP [1][2], both of which analyze on the basis of this polling system. In IPACT, the order of the data and the reservation interval are reversed using the polling system. IPACT gated service can be modeled using the gated service of the polling system. Because limited service is a method that restricts the data interval, it can be modeled using the limited service of the polling system. Note that the gated system and gated service are different things.

TABLE I. GATED SERVICE

| IPACT [5] | DR-MPCP [1][2] |
|---|---|
| Only those packets that arrived prior to the ONU's preceding reservation interval are transmitted. | In IPACT gated service, the transmission timing of the REPORT message is shifted. |

TABLE II. LIMITED SERVICE

| IPACT [5] | DR-MPCP [1][2] |
|---|---|
| Each ONU's data interval is limited by the maximum transmission window. | In IPACT limited service, the transmission timing of the REPORT message is shifted. |

## III. DR-MPCP

### A. System model

As shown in Fig. 2, it is assumed that in EPONs, $N$ ONUs are connected to an OLT through an optical splitter, and the distance between the OLT and each ONU is the same. Moreover, the arrival rate and service time of each packet are assumed to be independent. In the case of EPONs, uplink communication must consider the DBA in order to avoid the collision of packets. For these reason, we only focused on uplink communication. In this system, the OLT is controlled by cycle polling using DR-MPCP limited service. Let $T_{cycle}$ be one cycle time of the data and reservation intervals of all the ONUs. In limited service, the OLT allocates a data interval for each ONU. The maximum value of this data interval is the upper limit value $T_{max}$. Because the length of the data interval varies depending on the traffic demand, Tcycle also varies.

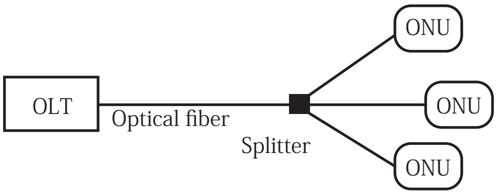

Fig. 2. System overview.

It is also assumed that a packet arriving at any of the ONUs waits in a queue until it receives the GATE message from the OLT and starts to be transmitted. The waiting packets are transmitted in first-in first-out (FIFO) order in accordance with the assigned data interval. It is assumed that the buffer size of each ONU is sufficiently larger than the amount of arriving packets and that there is no packet loss due to queue overflow. A guard time is set between the reservation interval of the ONU and the data interval of the next ONU. Further, the probability of a packet arriving at the queue of each ONU follows an independent Poisson distribution $\lambda/N$, and the primary and secondary moments of the packet service time are $\overline{X}$ and $\overline{X^2}$, respectively. Also, the primary and secondary moments of the reservation interval are $\overline{V}$ and $\overline{V^2}$, respectively, and the variance is $\sigma_v^2$. The traffic intensity of all ONU packets is assumed to be $\rho = \lambda\overline{X}$.

In the DR-MPCP method, the timing at which ONUs receive the GATE message ( as well as the timing at which REPORT messages are transmitted) is delayed. The amount by which it is delayed is the sum of the reservation and data intervals of $m$ ONUs $(0 \leq m < N)$. That is, immediately after the data interval of ONU $n$, the reservation interval of the $(N-m+n)$th ONU comes.

### B. Mean packet delay

Assuming that the mean packet delay of a packet is $\overline{W}$, it can be given by the expression $\overline{W} = \overline{W_F} + \overline{W_Q} + \overline{W_R}$. Here, $\overline{W_F}$ is the residual service time, i.e. the mean remaining time until an arrived packet's service time is complete. $\overline{W_Q}$ is the mean time for the transmissions of packets ahead of the arrived packet and $\overline{W_R}$ is the mean time for the reservations of packets ahead of an arrived packet.

Parameters $\overline{W_R}$ and $\overline{W_Q}$ are common among the polling system, IPACT, and DR-MPCP for gated service. However, $\overline{W_R}$ is a different expression [1][2]. Even if DR-MPCP is expanded for limited service, the only difference is that there is an upper limit on the length of the data interval. Thus, parameters $\overline{W_R}$ and $\overline{W_Q}$ use only the following Eq.s (1) and (2), and we derive only $\overline{W}_R^{dr,lim}$, meaning $W_R$ of DR-MPCP limited service. Here, the expressions of $\overline{W_R}$, $\overline{W_Q}$, and $\overline{W}_R^{dr,gt}$ in DR-MPCP gated service are shown below.

$$\overline{W}_F = \frac{\lambda\overline{X^2}}{2} + \frac{(1-\rho)\overline{V^2}}{2\overline{V}} \tag{1}$$

$$\overline{W}_Q = \rho\overline{W} \tag{2}$$

$$\overline{W}_R^{dr,gt} = \frac{1}{2}(3N - 2m - 1)\overline{V} \tag{3}$$

The mean packet delay in DR-MPCP gated service can be expressed as follows:

$$\overline{W}^{dr,gt} = \frac{\lambda\overline{X^2}}{2(1-\rho)} + \frac{(3N-\rho-2m)\overline{V}}{2(1-\rho)} + \frac{\sigma_v^2}{2\overline{V}}. \tag{4}$$

### C. Differences between gated and limited services

In EPONs, a guard interval is provided between the reservation and data intervals. The sum of the data and reservation intervals, including the guard interval, is called cycle time $T_{cycle}$. When this cycle time increases, the packet delay also increases. When this cycle time decreases, the proportion of the cycle time to the guard interval increases.

Let $T_{cycle\_max}$ be the maximum value of cycle time. It can be expressed as follows:

$$T_{cycle\_max} = N(T_{max} + \overline{V}). \tag{5}$$

Note that we assume that the guard interval is included in $\overline{V}$. In gated service, $T_{max}$ is set according to the buffer size of each ONU. However, $T_{cycle}$ for limited service is restricted by $T_{max}$.

## IV. ANALYSIS OF DR-MPCP LIMITED SERVICE

In DR-MPCP gated service, all packets that arrive before the REPORT message is transmitted can be transmitted in the data interval of the next cycle. However, gated service is not realistic. This is because it creates unfairness of transmission window arises among users. In limited service, if the arrived packets cannot all be transmitted in the data interval, the remaining packets are reserved again with the REPORT message of the next cycle.

### A. Upper bound of the mean packet delay

First, we analyzed the upper limit of the mean packet delay in DR-MPCP limited service. We assumed a traffic situation with a high load at which the data interval becomes $T_{max}$. The behavior of limited service is similar to that of gated service. In this paper, the upper bound of the limited service was analyzed using the gated service model [1][2].

Traffic situations can be roughly divided into two types: a low traffic load and a high traffic load. As shown in Fig. 3, $N$ users send packets, and the traffic in ONUs from 1th to $(m+1)$th is low. This traffic intensity $\tilde{\rho}$ is $\lambda\tilde{\overline{X}}$. In contrast, the traffic in ONUs from $N$th to $(m+2)$th is high. This traffic intensity $\rho'$ is $\lambda'\overline{X} > 1$. In this traffic situation, not all packets can be transmitted in a data interval because many packets arrive. This means that the data interval is the upper limit value. That is, the sum of each data and reservation interval is a fixed value $\tilde{V}$. Here, $\overline{V}$ used in the analysis of the gated service is also a fixed value. Thus, we can replace $\tilde{V}$ with $\overline{V}$. This $\tilde{V}$ can be written as $\tilde{V} = (N-m)\overline{V} + (N-m-1)T_{max}$ from Fig. 3. From this, the limited service model with an upper-bound traffic situation can be approximated using gated service with only one ONU.

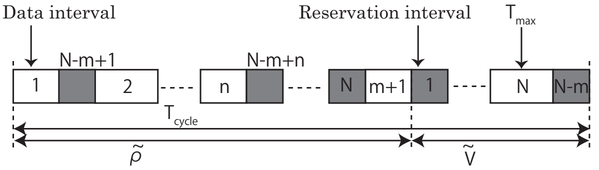

Fig. 3. DR-MPCP upper limit

This can be applied to Eq. (4) but with $N$, $\lambda$, $\rho$, $\overline{V}$, $\sigma_v^2$, and $m$ replaced with $\tilde{\lambda}$, $\tilde{\rho}$, $\tilde{V}$, $N\sigma_v^2$, and 0, respectively.

$$\overline{W}_{simp}^{dr,lim} = \frac{\tilde{\lambda}\overline{X^2}}{2(1-\tilde{\rho})} + \frac{(3-\tilde{\rho})\tilde{V}}{2(1-\tilde{\rho})} + \frac{N\sigma_v^2}{2\tilde{V}} \tag{6}$$

As shown in Fig. 4, we compared the theoretical results with simulation results. The number of ONUs is set to 16 and 32, and $m$ is set to 12 and 24, respectively. The bandwidth of the uplink communication $C_{up}$ is $1Gbps$. The guard time $t_g$ is $1\mu s$, and the REPORT message size $L_R$ is 64 bytes, as is the MPCP standard [4]. The mean reservation $\overline{V} = t_g + 8\frac{L_R}{C_{up}}$ is set to $1.512\mu s$ with $\sigma_v^2 = 0$. The packet payload size is distributed as 64 bytes (47%), 300 bytes (5%), 594 bytes (15%), 1300 bytes (5%), 1518 bytes (28%) between 64 bytes and 1518 bytes [8], with $\overline{X} = 5.090\mu s$ and $\overline{X^2} = 51.468(\mu s)^2$. The simulation code is written using MATLAB.

As shown in Fig. 4, the simulation and theoretical values are almost identical. This indicates our theory is valid. In addition, the mean packet delay increases sharply as the traffic density increases. However, this model cannot be applied data with an interval time less than $T_{max}$. Therefore, the next section performs theoretical analysis of mean packet delay when the data interval time is equal to or less than $T_{max}$.

## V. MEAN PACKET DELAY ANALYSIS OF DR-MPCP LIMITED SERVICE

With DR-MPCP limited service, the mean packet delay can be given by the expression $\overline{W}^{dr,lim} = \overline{W}_F +$

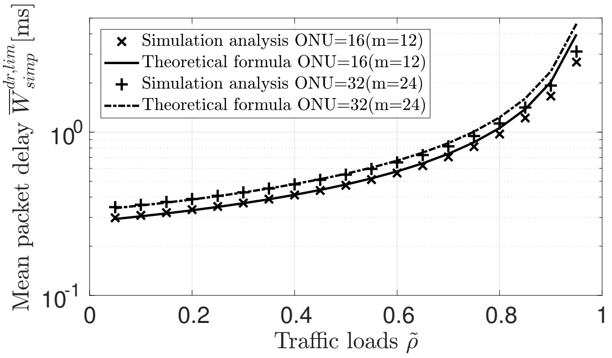

Fig. 4. Mean packet delay in the DR-MPCP upper-limit model.

$\overline{W_Q} + \overline{W}_R^{dr,lim}$. The mean packet delay of the limited service can be analyzed using the same $\overline{W_F}$ of Eq. (1) and $\overline{W_Q}$ of Eq. (2). This is because limited service is the same as gated service except for the upper value of the time for the data interval. Thus, we derive $\overline{W}_R^{dr,lim}$ by considering the difference from $\overline{W}_R^{dr,gt}$.

As shown in Fig. 5, the waiting time of an arrived packet falls into four categories $C_d = \{D_b; R_b; D_a; R_a\}$ on the basis of the time the packet arrive. Without loss of generality, we assume that an arriving packet is for the ONU 1 [7]. In the case of $D_b$, a packet arrives in the data interval before its ONU's REPORT message. In the case of $R_b$, a packet arrives in the reservation interval before its ONU's REPORT message. In the case of $D_a$, a packet arrives in the data interval after its ONU's REPORT message. In the case of $R_a$, a packet arrives in the reservation interval after its ONU's REPORT message. As shown in Table III, the probability of a packet arriving in a data interval is $\frac{\rho}{N}$, and the probability of a packet arriving in a reservation interval is $\frac{1-\rho}{N}$.

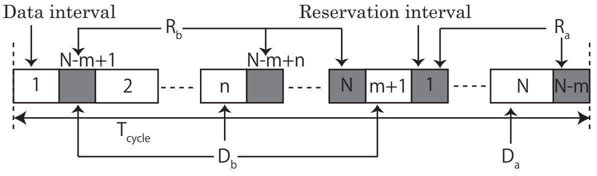

Fig. 5. Cases of packet arrival in first ONU in DR-MPCP

TABLE III. CLASSIFICATION OF PACKET ARRIVAL PROBABILITY OF $\overline{W}_R^{dr,gt}$ [1][2]

| $C_d$ | $\overline{W}_R^{dr}$ for DR-MPCP | Probability | Range of $n$ |
|---|---|---|---|
| $D_b$ | $(N-n+1)\overline{V}$ | $\frac{\rho}{N}$ | $n = 1, ..., m+1$ |
| $R_b$ | $(N-n)\overline{V}$ | $\frac{1-\rho}{N}$ | $n = 1, ..., m$ |
| $D_a$ | $(2N-n+1)\overline{V}$ | $\frac{\rho}{N}$ | $n = m+2, ..., N$ |
| $R_a$ | $(2N-n)\overline{V}$ | $\frac{1-\rho}{N}$ | $n = m+1, ..., N$ |

In limited service, the size of the transmission window is limited. If many packets arrive at an ONU, some cannot be transmitted within the transmission window and are instead transmitted in the the ONU's data interval in the next cycle. In this situation, additional cycles occur. Therefore, in limited services, it is necessary to newly analyze the additional cycle time.

Let $N_Q$ be the number of packets already queued in the queue of all the ONUs when a packet arrives. At this time, the average number of packets already waiting in each ONU can be written as $\frac{N_Q}{N}$. According to Little's law, it is equal to $\lambda\overline{W}$. That is, the average service time of packets already waiting in the queues of each ONU can be expressed by the following formula.

$$\frac{N_Q}{N} \times \overline{X} = \frac{\lambda\overline{WX}}{N} = \frac{\rho\overline{W}}{N} \tag{7}$$

In these words, the average of the number of cycles required to process the packets waiting in the queues of all ONUs can be expressed as $(\rho\overline{W}/N)/T_{max}$ by using the maximum value $T_{max}$ of the data interval.

However, in the case of $D_a$ or $R_a$ in Table III, the sum of the service time for arrive packets exceeds $T_{max}$. The packets that cannot be transmitted to the OLT in the cycle are handled in the next cycle. Therefore, the average number of cycles in $D_a$ and $R_a$ is $(\rho\overline{W}/N)/T_{max} - (N-m)/N$. Because the time for arrive packets in $D_a$ and $R_a$ is outside the data interval of ONU 1, the probability that the packet arrives in ONU 1 in these cases is shown as $(1-\rho/N)q$. Here, $q$ is the probability that the sum of the services time for the arrive packets requested by the REPORT message exceeds $T_{max}$. In this situation, excess packets are transmitted in the next cycle. In the case of $D_b$ or $R_b$, the average of the number of cycles is $(\rho\overline{W}/N)/T_{max}$ because the data interval of ONU 1 is less than $T_{max}$. The probability of packets arriving in these cases is $1-(1-\rho/N)q$.

Table IV shows the division packet arrival in these cases. The additional mean waiting time in DR-MPCP with cycle time added by the limitation of transmission window for the limited service can be expressed by the following equation:

$$\begin{aligned}\Delta\overline{W}_R^{dr,lim} &= \left\{\frac{\rho\overline{W}}{NT_{max}} \times (1-((1-\frac{\rho}{N})q))\right.\\ &\left.+ (\frac{\rho\overline{W}}{NT_{max}} - (\frac{N-m}{N})) \times ((1-\frac{\rho}{N})q)\right\} N\overline{V}\\ &= \left\{\frac{\rho\overline{W}}{NT_{max}} - (\frac{N-m}{N}) \times (1-\frac{\rho}{N})q\right\} N\overline{V}.\end{aligned}$$

where, $\Delta W_R^{di,lim} = W_R^{dr,lim} - W_R^{dr,gt}$. Thus, we can derive $W_R^{lim,lim}$,

$$\begin{aligned}\overline{W}_R^{dr,lim} = & \frac{(3N-2m-1)\overline{V}}{2} + \frac{\rho\overline{WV}}{T_{max}}\\ & -q(\frac{N-m}{N})(N-\rho)\overline{V}.\end{aligned} \tag{8}$$

TABLE IV. DR-MPCP CASES FOR LIMITED SERVICE.

| Cases | Average number of cycles | Probability |
|---|---|---|
| $D_b$ or $R_b$ | $(\rho\overline{W}/N)/T_{max}$ | $1-(1-\rho/N)q$ |
| $D_a$ or $R_a$ | $(\rho\overline{W}/N)/T_{max}-\frac{N-m}{N}$ | $(1-\rho/N)q$ |

Next, we derive the probability $q$. Let $T'$ be the average of the data interval that is satisfied by a value less than $T_{max}$, and the following equation holds.

$$\frac{\rho}{1-\rho}=q\frac{T_{max}}{\overline{V}}+(1-q)\frac{T'}{\overline{V}} \tag{9}$$

This formula can be summarized as follows:

$$\begin{aligned}\frac{\rho}{1-\rho}\overline{V}&=qT_{max}+T'-qT'=q(T_{max}-T')+T'\\ q=\frac{\frac{\rho}{1-\rho}\overline{V}-T'}{T_{max}-T'}&=\frac{\frac{\rho}{1-\rho}\overline{V}-T'+T_{max}-T_{max}}{T_{max}-T'}\\ &=1-\frac{T_{max}-\frac{\rho}{1-\rho}\overline{V}}{T_{max}-T'}.\end{aligned} \tag{10}$$

The parameter $T'$ is an unknown parameter. In this work, we use the approximation used in [7].

$$T_{max}-T'\approx T_{max} \tag{11}$$

By using Eq. 11, $q$ becomes as follows:

$$q\approx 1-\frac{\rho\overline{V}}{T_{max}(1-\rho)}. \tag{12}$$

Therefore, by substituting Eq. (12), the mean packet delay in DR-MPCP limited service is as follows:

$$\begin{aligned}\overline{W}^{dr,lim}&=\frac{\lambda\overline{X^2}+(3N-2m-\rho)\overline{V}}{2(1-\rho-\frac{\rho\overline{V}}{T_{max}})}\\ &-\frac{(N-m)(N-\rho)q\overline{V}}{(1-\rho-\frac{\rho\overline{V}}{T_{max}})}+\frac{(1-\rho)\sigma_v^2}{2\overline{V}(1-\rho-\frac{\rho\overline{V}}{T_{max}})}.\end{aligned} \tag{13}$$

## VI. NUMERICAL ANALYSIS

In this section, we compare the mean packet delay, Eq. (13) derived in the previous chapter with that obtained by simulation. Parameters for numerical analysis were set in the same way as in Section IV-A.

In general, if the distance from the OLT to the ONU increases, the RTT (i.e. the time from sending the REPORT message to returning the GATE message) for the reservation of the transmission also increases. The time form transmitting the REPORT message (reserving a packet) to transmitting the reserved packet with DR-MPCP is shorter than that with IPACT. If the RTT exceeds than the time from packet reservation to packet transmission, an idle interval occurs because packets cannot be sent until the GATE message arrives. Therefore, in the DR-MPCP system, it is necessary to take this into consideration when setting the shifting amount $m$. In this numerical analysis, $m$ with RTT taken into consideration is as follows:

$$m^*=\max\left(\left\lfloor\frac{(\overline{T_{cycle}}-RTT)\times N}{\overline{T_{cycle}}}\right\rfloor,0\right), \tag{14}$$

where, $\overline{T_{cycle}}$ is the mean value of $T_{cycle}$ for each ONU. In this study, it is assumed that propagation delay occurs only in RTT. RTT was calculated using the group refractive index $n_g=1.46$ of quartz optical fiber [9]. Further, $T_{max}$ was set after setting the maximum value of the cycle time as $T_{cycle\_max}=2[ms]$ [5]. From Eq. (5), $T_{max}$ is set as follows:

$$T_{max}=\frac{T_{cycle\_max}}{N}-\overline{V}[s]. \tag{15}$$

Table V gives the value of $m^*$ using Eq. (14). However, when $\rho$ is 0.55 or less, $m^*$ is always 0, so it is omitted from the table. The results in this table reveal that a range of $m^*=0$ exists. When $m*=0$, DR-MPCP is the same as IPACT, which does not shift the REPORT message.

TABLE V. $m^*$ (DISTANCE FROM OLT TO ONU IS 10 $km$)

| N / $\rho$ | 0.55 | 0.6 | 0.65 | 0.7 | 0.75 | 0.8 | 0.85 | 0.9 | 0.95 |
|---|---|---|---|---|---|---|---|---|---|
| 16 | 0 | 0 | 0 | 0 | 0 | 3 | 6 | 9 | 12 |
| 32 | 3 | 6 | 9 | 12 | 15 | 19 | 22 | 25 | 28 |

The theoretical formula (13) of $\overline{W}^{dr,lim}$ and the simulation values were compared on the basis on the above traffic parameters. The results are shown in Fig. 6.

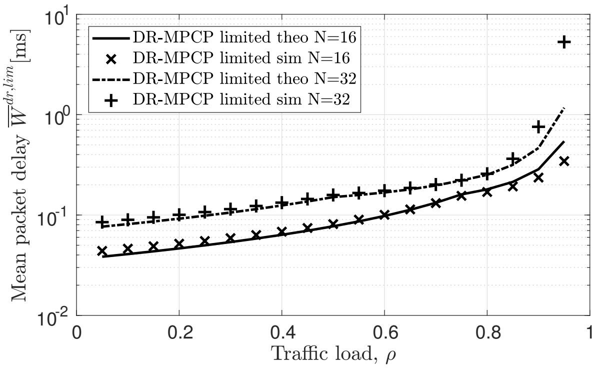

Fig. 6. Mean packet delay of DR-MPCP limited service. Distance from OLT to ONU is 10 $km$.

As shown in Fig. 6, the simulation and theoretical results match closely. However, when the traffic intensity is high, the value of the theoretical expression deviates from the simulation value. This is because the approximation formula (11) assumes that the processing time for packets arriving at the ONU is equivalent to the set $T_{max}$. However, in a real network, if the traffic intensity is high, the value of $T'$ also increases. In that case, Eq. (11) does not hold. That is, it can be considered that the value of $q$ in Eq. (12) is estimated to be lower than its actual value. Therefore, in order to approximate the theoretical formula to the simulation value, it is necessary to appropriately set the value of $T'$(that is, $q$).

Next, we analyze the case where the distance between the OLT and the ONU is changed, shown in Fig. 7. In this analysis, from the values in Table VI, the ONU selects traffic $\rho = 0.8$ in which $m^*$ is not 0 in both $N = 16$ and 32. The value of $m$ in this figure is shown in Table VI. As shown in Fig. 7, the value of the mean packet delay increases as the distance increases. This is because the RTT increases as the distance increases. In this traffic situation, the allowable shifting amount $m$ must be set to 0, as is the case for IPACT. In these words, as the distance from the ONU to the OLT increases, the effectiveness of DR-MPCP's decrease in the delay time in comparison with IPACT decreases.

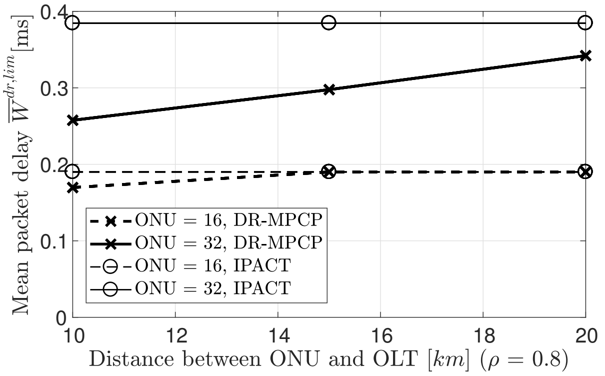

Fig. 7. Mean packet delay of DR-MPCP limited service

TABLE VI. MAXIMUM VALUE OF $m$ IN RANGE WHERE IDLE INTERVAL CANNOT BE FORMED WHEN CONSIDERING RTT($\rho = 0.8$)

| N / Distance from OLT to ONU [$km$] | 10 | 15 | 20 |
|---|---|---|---|
| 16 | 3 | 0 | 0 |
| 32 | 19 | 12 | 6 |

## VII. CONCLUSION

In this research, we derived the mean packet delay of DR-MPCP limited service and showed the validity of our theoretical analysis by comparing it with a simulation. However, we found that the value of our theoretical analysis became less accurate when the traffic intensity was high. In the future, we will improve this part of our theoretical analysis. In addition, as a result of comparing the mean packet delay while consider the RTT according to the distance from the OLT to the ONU, we found that the effectiveness of the DR-MPCP increases as the distance decreases. In the future, we will propose an extended DR-MPCP to decrease mean packet delay even for long distance. Moreover, the result of this research can be applicable not only to EPON but also to NG-PON2 [10] and others. For this reason, we would like to adapt to other systems in the future. Finally, since the traffic pattern assumed in this work is single, we would like to extend it in the case of multi-dimensional traffic [11] in the future.

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## REFERENCES

[1] S. Miyata, K. Baba, K. Yamaoka, H. Kinoshita, "DR-MPCP: Delayed REPORT message for MultiPoint Control Protocol in EPON," Proc. of IEEE RNDM 2015, pp. 237-242, Oct. 2015.

[2] S. Miyata, K. Baba, K. Yamaoka, "Exact mean packet delay for Delayed REPORT message MultiPoint Control Protocol in EPON," Journal of Optical Communications and Networking, IEEE/OSA Journal of Optical Communications and Networking, vol. 10, issue. 3, pp. 209 – 219, March. 2018.

[3] Derek Nesset, "PON Roadmap [Invited]," Journal of Optical Communications and Networking Vol. 9, Issue 1, pp. A71-A76, Jan. 2017.

[4] G. Kramer, "Ethernet Passive Optical Networks," New York: Mc-Graw Hill, 2005.

[5] G. Kramer and B. Mukherjee, "IPACT: A Dynamic Protocol for an Ethernet PON (EPON)," IEEE Communications Magazine, Feb. 2002.

[6] D. P. Bertsekas and R. G. Gallager, *Data Networks*, 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, 1992.

[7] S. Bharati, P. Saengudomlert, "Analysis of Mean Packet Delay for Dynamic Bandwidth Allocation Algiorithms in EPONs," IEEE, Jornal Of Lightware Technology, Vol. 28, No.23, pp. 3454-3462, Dec. 1, 2010.

[8] C. G. Park et al., "Packet delay analysis of symmetric gated polling system for DBA scheme in an EPON," Telecommun. Syst., vol.30, no. 1-3, pp. 13-34, 2005.

[9] J. M. Senior, *Optical Fiber Communications Principles and Practice,* Prentice Hall: PEARSON, 2009.

[10] ITU-T Recommendation G.989 :" 40–Gigabit–capable passive optical networks (NG-PON2): Definitions, abbreviations and acronyms, " 2015.

[11] M. D. Logothetis, I. D. Moscholios, A. C. Boucouvalas and J. S. Vardakas, " Delay Performance of WDM-EPON for Multi-dimensional Traffic Under the IPACT Fixed Service and the Multi-Point Control Protocol", Proc. of 2nd European Teletraffic Seminar, Blekinge Institute of Technology, Karlskrona, Sweden, 30 September - 2 October, 2013.