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Determination of Number of Upstream Subcarriers to Minimize Cycle Time in OFDMA-PON Using Interleaved Polling Method

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Abstract

In an orthogonal frequency-division multiple access passive optical network (OFDMA-PON) using an interleaved polling method, delay is increased by long cycle time, where the cycle time is the time duration between the current and next upstream transmissions. The cycle time is affected by the number of upstream subcarriers for an optical network unit (ONU). Available subcarriers are limited due to the system implementation cost, but the small number of upstream subcarriers increases the cycle time in sending the same amount of data. In this paper, we determine the number of upstream subcarriers to guarantee low delay under a gated service discipline.

Keywords: *Delay, Cycle time, Interleaved polling, OFDMA-PON, Subcarriers*

1. Introduction

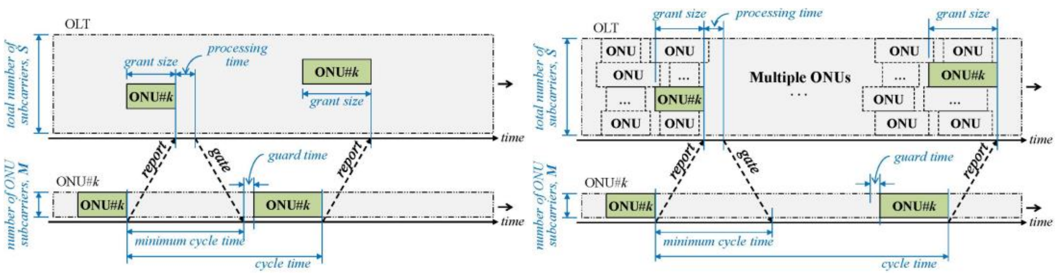
Next-generation passive optical networks (PONs) need to provide a large capacity in an extended coverage, in order to reduce the operation expenditure by decreasing the number of central offices along the optical link [1]. However, the deployment cost of 40+ Gb/s time-division multiple access (TDMA) PONs is expensive due to the scarcity of available high-speed optical components and burst-mode receivers [2-3]. Wavelength division multiplexing (WDM) PONs require modifications for network expansion due to the lack of flexibility and dynamicity [4]. To overcome these problems in an economical way, hybrid WDM/TDMA PONs, time- and wavelength-division multiplexed (TWDM) PONs, and orthogonal frequency-division multiple access (OFDMA) PONs have been studied [3-4]. As one of next-generation optical access technologies, the OFDMA-PONs enlarge the resources (*i.e.*, network bandwidth) by efficiently utilizing available spectra and extend their transmission distances with the advantage of high resilience to fiber dispersions [3].

In OFDMA-PONs, a medium access control (MAC) ensures collision-free access by allocating subcarriers and time resources to ONUs [3-4]. In simulations of [3], it is found that the number of upstream subcarriers for an optical network unit (ONU) is related to the network delay. In [4], the delay is analyzed with cycle time in accordance with the number of upstream subcarriers, by using averaged value approaches in [5-6], at an OFDMA-PON using an interleaved polling method, where the cycle time is the time duration between the current and next upstream transmissions. According to simulation results of [4], the cycle time is increased when the number of upstream subcarriers is too small or big. Finding the number of upstream subcarriers to guarantee a tolerable cycle time is meaningful. In this paper, the estimation to the cycle time in [3] is simplified to approximately and quickly determine the number of upstream subcarriers to guarantee low delay.

The remainder is organized as follows. In Section II, mathematical formulas are presented to find the effective number of upstream subcarriers by considering the cycle time at light and heavy load conditions under a gated service discipline, which grants the amount of bytes requested from ONUs to the corresponding ONU. In Section III, the simulation results are shown. Section IV concludes this paper.

2. Number of Subcarriers to Minimize Cycle Time

To estimate cycle time, we start from the well-defined OFDMA-PON MAC framework presented in [2-3]. The MAC framework supports two-dimension (2-D) resource (*i.e.*, subcarriers, time) allocation based on the report/gate mechanism of 10-gigabit Ethernet PON (10G-EPON). In this mechanism, a *report* message is used to convey the queue status information of each ONU to the optical line terminal (OLT) and a *gate* message to inform the 2-D bandwidth-map (*i.e.*, low subcarrier index, high subcarrier index, start time, and stop time) to the ONUs. We assume the OFDMA-PON with N ONUs to be logically located in the same distance (after a ranging process). Here, let S and M ($\leq S$) be the total number of upstream subcarriers controlled by the OLT and the maximum number of available subcarriers for each ONU upstream transmission, respectively. For simplicity, it is further assumed that all the ONUs have the same number of upstream subcarriers and that the value of M is chosen as a divisor of S. Note that bandwidth contention among the ONUs occurs when the number of subcarriers to be controlled is less than the total number of subcarriers (*i.e.*, $S < M{\cdot}N$). For $S \geq M{\cdot}N$, each ONU can use M subcarriers regardless of access time. For the estimation, we used the interleaved polling method under a gated service discipline to distribute the upstream bandwidth among the ONUs, which is the same as the basic EPON approach. In the OFDMA-PON, the cycle time to an ONU is determined by the time duration required for the interleaved bandwidth grants of other ONUs. However, the cycle time must be larger than the minimum cycle time C_{min} determined by adding processing time for generating and interpreting the report and gate messages round-trip time (RTT). Therefore, we divided the cycle time into two cases, light and heavy loads, as shown in Figure 1, denoted using subscripts L and H, respectively.



(a) (b)

Figure 1. Illustrations of Cycle Times Under (a) Light and (b) Heavy Loads

For the light load, Figure 1(a) shows that the aggregated bandwidth of the ONUs' grant is less than the bandwidth during the time added by the minimum cycle time, based on the time duration of the averaged grant of the ONUs. With the assumption that each ONU requires a guard time in its turn, the cycle time (C_{L_k}) of ONU-#k is determined by the summation of the minimum cycle time (C_{min}), guard time duration (T_{guard}), and averaged time duration (G_{L_k}) corresponding to the bandwidth grant for upstream transmission, *i.e.*, $C_{L_k} = C_{min} + T_{guard} + G_{L_k}$. Then, the averaged cycle time $E[C_{L_k}]$ in the network is given by taking the average of the cycle times of N ONUs, *i.e.*, $E[C_{L_k}] = (1/N){\cdot}\sum_{k=1}^{N} C_{L_k}$, such that

$$E[C_{L_k}] = C_{\min} + T_{guard} + \frac{1}{N} \sum_{k=1}^{N} G_{L_k}. \tag{1}$$

In (1), the grant time duration (G_{L_k}) varies depending on the modulation format of the ONU upstream subcarriers. With the assumption that traffic loads among N ONUs are equally distributed, (1) can be rewritten by grouping the ONUs based on their modulation formats as

$$E[C_{L_k}] = C_{\min} + T_{guard} + \frac{1}{N} \cdot \sum_{\text{all } m} \left(N_m \cdot G_{L,m}\right), \tag{2}$$

Where m is the number of modulation format levels (*e.g.*, m = 4 for 4QAM), and N_m and $G_{L,m}$ are the number of groups and averaged grant time duration of the group with the same value of m, respectively. To obtain the averaged cycle time, we first need to consider the relation between $E[C_{L_k}]$ and $G_{L,m}$. Since the ONU reports its own queue length for each polling cycle, the averaged $G_{L,m}$ is approximately equal to the time duration for transmitting generated bytes at a rate α [bits/s] during $E[C_{L_k}]$ through M subcarriers having a rate R_m per single subcarrier, *i.e.*, $G_{L,m} = \alpha \cdot E[C_{L_k}] / (M \cdot R_m)$. Then, by substituting $G_{L,m}$ in (2) and solving for $E[C_{L_k}]$, the averaged cycle time under light loads can be obtained as

$$E[C_{L_k}] = \frac{M \cdot N \cdot \left(C_{\min} + T_{guard}\right)}{M \cdot N - \alpha \cdot \sum_{\text{all } m} \left(N_m / R_m\right)}. \tag{3}$$

Note that since the cycle time $E[C_{L_k}]$ must be a positive value, (3) holds for $\alpha < M \cdot N / (\sum_{\text{all } m} N_m / R_m)$.

For the heavy load case, since the time duration required to resolve the aggregated bandwidth of all ONU grants is larger than $E[C_{L_k}]$, the cycle time (C_{H_k}) of ONU-#k increases based on time required for the parallel interleaved grants of other ONUs, as shown in Figure 1(b). Since the upstream bandwidth under heavy loads is fully utilized by the ONUs, the averaged cycle time $E[C_{H_k}]$ can be obtained by dividing the time duration required for all ONU upstream transmissions using a single subcarrier by S subcarriers. Then, when the ONU uses M subcarriers for short delay, $E[C_{H_k}]$ can be expressed as

$$E[C_{H_k}] = \frac{1}{S} \cdot \sum_{k=1}^{N} M \cdot \left(T_{guard} + G_{H_k}\right), \tag{4}$$

Where G_{H_k} is the averaged time duration of the bandwidth grant for the upstream transmission of ONU-#k. Similar to the process of the light load case, (4) can be extended to a network having ONUs using different modulation formats. By grouping the ONUs, (4) can be rewritten as

$$E[C_{H_k}] = \frac{M \cdot N}{S} \cdot T_{guard} + \frac{M}{S} \cdot \sum_{\text{all } m} \left(N_m \cdot G_{H,m}\right), \tag{5}$$

Where $G_{H,m}$ is the averaged grant time duration of grouped ONUs with the same value of m. The averaged time duration $G_{H,m}$ is then determined using $G_{H,m} = \alpha \cdot E[C_{H_k}] / (M \cdot R_m)$. By substituting $G_{H,m}$ into (5) and solving for $E[C_{H_k}]$, we can also obtain the averaged cycle time at heavy loads, as

$$E[C_{H_k}] = \frac{M \cdot N \cdot T_{guard}}{S - \alpha \cdot \sum_{\text{all } m} \left(N_m / R_m \right)}. \quad (6)$$

Equation (6) holds for $\alpha < S / (\sum_{\text{all } m} N_m / R_m)$ to guarantee a positive cycle time value. Ultimately, the averaged cycle time for both the light and heavy load cases can be determined by $\max(E[C_{L_k}], E[C_{H_k}])$.

3. Simulation Results

For cycle time estimation, an OFDMA-PON with S = 256 and N = 128 at a distance of 20 km having an RTT of 200 μs (and 100 km having RTT of 1 ms) was modeled. The processing and guard times are set to 35 μs [6] and 1.440 μs [7], respectively; the guard time refers to that of a TDM-PON. The transmission rate of a single subcarrier with BPSK modulation is set to 39 Mbits/s, corresponding to a total network capacity of 10 Gbits/s for 256 subcarriers.

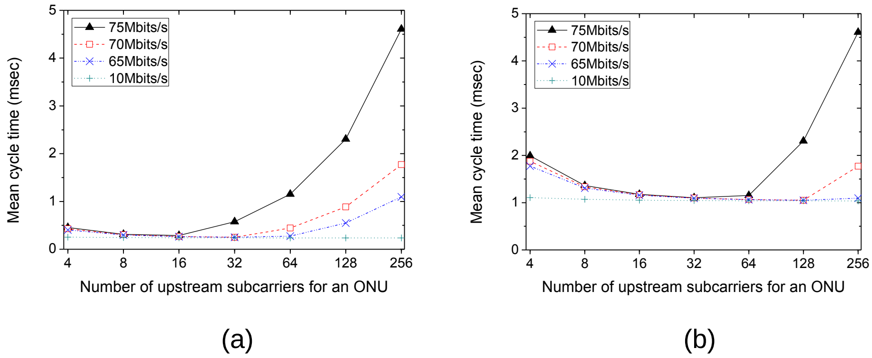
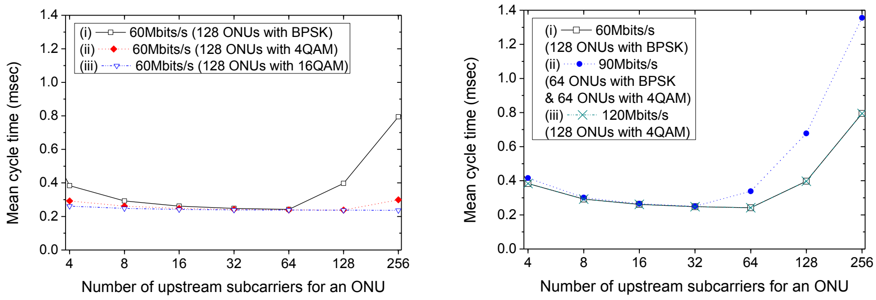


Figure 2. Cycle Times at Different Distances of (a) 20 km, and (b) 100 km

Figure 2 shows the averaged cycle time as a function of the number of upstream subcarriers, with averaged traffic generation rates of 10 Mbits/s, 65 Mbits/s, 70 Mbits/s, and 75 Mbits/s for an ONU. Here, BPSK modulation was also assumed. The averaged cycle time under light load displays relatively low and flat values over the entire range of subcarrier numbers because the ONU bandwidth grants can be accommodated within the bandwidth during the minimum cycle time, which is much larger than the averaged grant time of a single ONU. On the other hand, the averaged cycle times under heavy loads fluctuated. The cycle time for a small number of upstream subcarriers (*e.g.*, M = 4) is decreased due to the sufficient number of subcarriers, and then increased with a large number of subcarriers (*e.g.*, M > 16 at 75 Mbits/s, and M > 32 at 60 Mbits/s and 65 Mbits/s). This increase is due to waste of the upstream bandwidth incurred by assigning guard bandwidths to surplus subcarriers. In other words, the number minimizing the cycle time is should be estimated. At the heavy load, this increase is steeper at 100 km than at 20 km because the size of the bandwidth request for the queued data during the cycle time increases with the transmission distance. In addition, though the dependence on the number of subcarriers is similar in both cases, the increase for longer distances starts with larger subcarriers (Figure 2), *i.e.*, M = 32 at 20 km and 128 at 100 km for 70 Mbit/s. This result also can be utilized in allocating subcarriers, in order to reduce the cycle time. For example, when the number of ONU upstream subcarriers is about 128, we can set the allocation limit to 65 Mbits/s or 70 Mbits/s to prevent the cycle time from being largely increased.



(a) (b)

Figure 3. Cycle Time at Different Modulation Formats for (a) the same (60 Mbit/s), and (b) Different (60, 90, 120 Mbits/s) Upstream Service Rates

Next, we simulated the dependence of the cycle time on the modulation format for the 20 km case. Figure 3(a) presents the averaged cycle times for BPSK, 4QAM, and 16QAM to 128 ONUs required to support the upstream service rate of 60 Mbits/s. The figure shows that the number of subcarriers corresponding to the minimum averaged cycle time increases with the modulation format levels. That is, the number 64 for BPSK increases to 128 and 256 for 4QAM and 16QAM, respectively.

We also investigated the case of using different modulation formats between ONUs (Figure 3(b)). The line (iii) for 4QAM modulation matches that of (i) for BPSK because though the traffic generation rate doubles from 60 Mbits/s, the performance is also doubled by 4QAM. However, in the case of accommodating hybrid formats, *e.g.*, BPSK and 4QAM, line (ii) does not match lines (i) and (iii), even though 64 ONUs use BPSK and the other 64 ONUs use 4QAM. This difference is due to the fact that the time duration for the upstream transmission is reduced by using the high-level modulation formats for 64 ONUs, whereas the upstream bandwidth gain in terms of time should be redistributed to all 128 ONUs as fairly as possible. In other words, if the upstream bandwidth gain is provided to the ONUs with 4QAM, the cycle time will match lines (i) and (iii). As a result, the number of subcarriers corresponding to the minimum cycle time is decreased from 64 to 32, as shown in Figure 3(b).

4. Conclusion

We investigated the dependence of the cycle time on upstream carriers for both transmission distance and modulation format. The simulation results showed that the number of subcarriers should be increased for a longer distance in order to maintain the same cycle time, and that a large number of subcarriers can be accommodated without increasing the cycle time by using high-level modulation formats. In addition, we found that the number corresponding to the minimum cycle time is decreased when using a hybrid form of different modulation formats. As such, these results can be applied to OFDMA-PONs to extend their reach or to support ONUs using different modulation formats.

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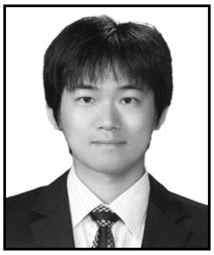

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