Staged optimization algorithms based MAC dynamic bandwidth allocation for OFDMA-PON

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Abstract

Orthogonal frequency division multiple access passive optical network (OFDMA-PON) has been considered as a promising solution for next-generation PONs due to its high spectral efficiency and flexible bandwidth allocation scheme. In order to take full advantage of these merits of OFDMA-PON, a high-efficiency medium access control (MAC) dynamic bandwidth allocation (DBA) scheme is needed. In this paper, we propose two DBA algorithms which can act on two different stages of a resource allocation process. To achieve higher bandwidth utilization and ensure the equity of ONUs, we propose a DBA algorithm based on frame structure for the stage of physical layer mapping. Targeting the global quality of service (QoS) of OFDMA-PON, we propose a full-range DBA algorithm with service level agreement (SLA) and class of service (CoS) for the stage of bandwidth allocation arbitration. The performance of the proposed MAC DBA scheme containing these two algorithms is evaluated using numerical simulations. Simulations of a 15 Gbps network with 1024 subcarriers and 32 ONUs demonstrate the maximum network throughput of 14.87 Gbps and the maximum packet delay of 1.45 ms for the highest priority CoS under high load condition.

1. Introduction

With the exponentially growing user-side demand for bandwidth services, such as high-definition television (HDTV), HD video conferencing, cloud and peer to peer, the passive optical network has required a higher access data rate [1]. To meet such demand, OFDMA-PON has been a promising candidate of next-generation PONs because of its advantages such as high transmission capacity, high spectral efficiency and flexible bandwidth allocation scheme [2–4]. Targeting the higher spectral efficiency of OFDMA, bit-and-power loading (BPL) provides higher level m-QAM (m is the variable level of QAM) format for each individual subcarrier [5]. K. Kanonakis proposed a cross-layer optimization algorithm to enhance the QoS in [6]. This algorithm can reasonably adjust the MAC DBA schemes according to the results of BPL.

There have been related works focusing on the MAC layer scheme [7–9]. W. Wei proposed two types of MAC scheme, namely fixed burst transmission (FBT) and dynamic circuit transmission (DCT) respectively in [8]. The FBT scheme, for the purpose of achieving the statistical multiplexing gain of OFDMA, treats each data transmission as a fixed burst, and employs the interleaved polling with adaptive cycle time (IPACT) [10] algorithm. DCT treats each data transmission as a dynamic short-lived/long-lived circuit, and employs bandwidth estimation to provide the target QoS. J. Zhang proposed a novel MAC scheme which can eliminate the asynchronous requirement but also exploit the traffic statistical gain in [9]. More recently, W. Lim proposed a DBA algorithm that allows the optical line terminal (OLT) to grant the optical network units (ONUs) bandwidth with both status and non-status based algorithms in [7]. The non-status based algorithm implements a monitoring mechanism to monitor the amount of data in a duration of 2 ms. The OLT can estimate the required bandwidth of each ONU according to the monitoring information. The status based algorithm supports the OLT to assign bandwidth relying on the requests of the ONUs that belong to different SLAs, so that it can enhance the QoS of the OFDMA-PON.

According to the previous works, the DBA process can be divided into two closely related stages: the physical layer mapping based DBA (PMB-DBA), which decides the two-dimensional mapping operations, and the ONUs requesting based DBA (ORB-DBA), which arbitrates the data sizes transmitted in the following cycle based on the reports. The PMB-DBA is a more comprehensive and flexible process in OFDMA-PON including the 1-dimension to 2-dimension mapping. We can make full use of it to exploit the statistical multiplexing gain and enhance the QoS [6]. However, the OFDMA frame structure, which has barely been taken into consideration in previous works, is the important prerequisite to develop an efficient PMB-DBA algorithm [11]. For the ORB-DBA, the

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most of the previous works are not based on an efficient PMB-DBA algorithm in OFDMA-PON. They only focus on the heavy load condition so that cannot ensure global QoS of the system. So in order to increase the bandwidth utilization and enhance the QoS, a high-efficiency DBA scheme including an efficient PMB-DBA algorithm and an efficient ORB-DBA algorithm is necessary.

In this paper, for the first time it is proposed a PMB-DBA algorithm with the consideration of OFDMA frame structure. By taking full advantages of OFDMA frame structure and a new dynamic sub-carriers assignment for minimum bandwidth waste (MBW-DSA) algorithm, we can ensure the equity of ONUs and achieve higher system bandwidth utilization. In order to further ensure the global QoS and match the proposed PMB-DBA algorithm, we propose a full-range ORB-DBA algorithm (which can be implemented from light load condition to heavy load condition) with SLA and CoS for OFDMA-PON. The multistage allocation method (MAM) introduced into ORB-DBA algorithm ensures strict priority-based assignment of the bandwidth.

2. OFDMA-PON architecture and physical mapping characteristics

The topology of point-to-multipoint OFDMA-PON is shown in Fig. 1 [12,13]. The system consists of an OLT located at the central office (CO) and several ONUs at the client side. The downstream data traffics are transmitted to all ONUs from the CO under the controlling of the OLT. The upstream transmission is much more complicated, because the OLT needs to collect the queue status of each ONU before resource allocation. Therefore, this paper mainly focuses on the process of upstream resource allocation. ONUs are divided into three SLAs (SLA1 to SLA3 exhibit high to low superiority). In each ONU, there are three queues serving three priority classes of service (CoS0 to CoS2 exhibit high to low superiority) as shown in Fig. 1. ONUs can request their queue status intermittently. The OLT arbitrates the data sizes that will be transmitted in the following cycle relying on the ORB-DBA algorithm. Fig. 2 depicts a series of upstream resource blocks in terms of time domain symbols on x axis, frequency domain sub-carriers on y axis. In order to describe the PMB-DBA algorithm more clearly, in Figs 2 and 3, there are only 15 sub-carriers (usually many times to the number in the practical system) and eight symbols (the first one is used as preamble symbol) included in an OFDMA frame. An integrant inter-cycle gap (ICG) is added between two adjoining cycles and an optional inter-frame gap (IFG) may be added between two adjoining frames. The main purposes of these gaps are to avoid bit errors caused by the noise generated in the process of lasers switching and prevent data collision. The data traffics from upper layers will be mapped to these frames under the control of PMB-DBA algorithm.

It is worth mentioning that a fixed frame structure can guarantee the fact that the physical layer has a constant overhead and delay. The length of an OFDMA frame is the unit of granularity for DBA, i.e., a scheduling cycle must consist of one or more intact OFDMA frames. The number of symbols in an OFDMA frame, the preamble symbols and the size of the upstream data symbols are not the focus of this work. On the other hand, in a single frame, a certain sub-carrier cannot be occupied in burst manner by different ONUs, since preamble symbols and an IFG are needed to avoid the data collision and the interference introduced by lasers switching noise. Moreover, one or more dedicated sub-carriers will be served for control channels as in [8]. The focus of this paper is the DBA process including bandwidth arbitration and data mapping, so we only concentrate on the data sub-carriers in this paper. The unified scheduling algorithm which is based on control channels will be studied in the further research.

3. Staged optimization algorithms based MAC DBA scheme

3.1. Principle of proposed PMB-DBA scheme

Fig. 3 illustrates the proposed PMB-DBA algorithm. An elastic cycle scheme is introduced to achieve higher bandwidth utilization. Each sub-carrier is fixedly allocated to an ONU in a cycle (in different cycles, the sub-carrier can be allocated to other ONUs) as shown in Fig. 3(a). It ensures the equity of ONUs because all of the ONUs send data traffics at the same time window. The fixed sub-carriers allocation scheme in a cycle reduces the complexity of the OLT receiver, because the receiver does not need to handle too much complex information both in time and frequency domains. Compared with the conventional schemes, more significant is that the algorithm can avoid lasers switching and further save bandwidth due to null IFG in a cycle. Compared with the way mapping data from different ONUs in time order, this algorithm applies the mode of offline report handling which is conducive to the unified scheduling of full-range ORB-DBA algorithm.

In order to further simplify the complexity of MAC control frames and reduce the guard band consumption [6], the mapping process should minimize the number of sub-carrier groups assigned to different ONUs. With the influence of frequency response roll-off, system signal noise ratio (SNR) response, etc., bit loading over all sub-carriers presents a ladder-like distribution character [5]. So as the example shown in Fig. 3(b), in the process of mapping, a dedicated ONU will occupy a series of consecutive sub-carriers with the same QAM format based on the ladder-like distribution. Its benefits will be highlighted when more sub-carriers are applied.

Moreover, for the purpose of enhancing the QoS, an ONU will transmit higher priority class of service first and it works independently. If there are too many transmitters transmitting data
at the same time, the phase noise will cause the bit error rate (BER) greater than the FEC limit \(3.8 \times 10^{-3}\) [14]. So the transmitters limit is necessary to improve the system performance. When the number of transmitters is greater than the transmitters limit, sub-cycles will be implemented as shown in Fig. 3(c). In [14], C. Ruprecht demonstrated that the transmitters limit is 16 if the system do not introduce the trellis coded modulation (TCM) combined with an additional erbium-doped fiber amplifier (EDFA). For simplicity, the transmitters limit is set to 3 for example in Fig. 3(c). When there are five ONUs need to transmit data in this cycle, the OLT will arrange ONUs to transmit data in two sub-cycles based on their SLAs.

It also should be noticed that the granularity of sub-carrier allocation is determined by the capacity of each sub-carrier. Thereupon different sub-carriers allocation schemes will cause different degrees of bandwidth waste such as the description in Fig. 3(d). In order to squeeze such waste part as small as possible, a MBW-DSA algorithm tailored for this PMB-DBA algorithm is proposed. The MBW-DSA algorithm not only introduces adaptive cycle time scheme into the PMB-DBA algorithm, but it also can be applied in a cycle or a sub-cycle. This MBW-DSA algorithm is described below.
We let $N$ data sub-carriers be assigned to $K$ ONUs. Each sub-carrier $n$ ($s_n$, $n = 1, ..., N$) only can be assigned to a fixed ONU $k$ ($ONU_k, k = 1, ..., K$) in a cycle or a sub-cycle. The OFDM scheme can adopt intensity modulation/direct detection (IM/DD) or coherent detection. $C_n = (b/N)\log_2 m$ ($b$ is the signal bandwidth) depicts the capacity of $s_n$, $C_n = (x/2N)\log_2 m$ ($x$ is the sampling rate of ADC/DAC) can depict the capacity of $s_n$ when IM/DD is adopted. $C = \sum_{n=1}^{N} C_n$ depicts the total upstream capacity. Make $G_k$ to be the granted bandwidth for ONU$_k$ after the ORB-DBA process, and $G = \sum_{k=1}^{K} G_k$ to be the total granted bandwidth for all ONUs. After the allocation of sub-carriers, each ONU having data to transmit can be assigned one or more sub-carriers. The upstream interface capacity of ONU$_k$ can be defined as

$$C_k = \sum_{n=1}^{N} c_{k,n} C_n$$  \hspace{1cm} (1)

subject to

$$c_{k,n} \in \{0, 1\} \quad \forall k, n$$  \hspace{1cm} (2)

$$\sum_{k=1}^{K} c_{k,n} = 1 \quad \forall n$$  \hspace{1cm} (3)

where $c_{k,n}$ is the indicator of sub-carriers assignment. $c_{k,n} = 1$ indicates that $s_n$ is assigned to ONU$_k$. Eq. (2) ensures the correct value for MBW-DSA and Eq. (3) ensures each sub-carrier can only be assigned to a single ONU in a cycle or a sub-cycle. Let $T_c$ be the cycle time or the sub-cycle time, so

$$T_c = \left[ \frac{\max C_k}{\bar{c}_k} \right] \times T_f$$  \hspace{1cm} (4)

where $T_f$ is the time length of an OFDMA frame. Eq. (4) ensures the minimum time window with a sub-carriers allocation result and an integral number of OFDMA frames in the transmission window. The ideal cycle time that ignores the sub-carrier capacity granularity and the frame length granularity is formulated as $T_{ideal} = G/C$. $T_c$ and $T_{ideal}$ are depicted in Fig. 3(d). The objective of MBW-DSA is formulated as

$$\min \{CC_c - CT_{ideal}\}. \hspace{1cm} (5)$$

3.2. Proposed full-range ORB-DBA algorithm with SLA and CoS

After the OLT receives the queue status of ONUs, it will run the full-range ORB-DBA algorithm which can optimize the packet delay and the jitter performance of higher priority CoS from higher SLA ONUs in any network load condition. With knowing about the dynamic range of cycle time $T_{min}$ to $T_{max}$, the minimum scheduling bandwidth and the maximum scheduling bandwidth can be represented as $B_{min} = T_{min} \times C$ and $B_{max} = T_{max} \times C$. Assume that $R$ is the total bandwidth requirement of ONUs and $R^s_{ONU_k}$ ($s$ is the indicator of SLAs) is the bandwidth requirement of ONU$_k$, they are formulated as:

$$R = \sum_{c=0}^{3} \sum_{k=1}^{K} R^s_{c,k}$$  \hspace{1cm} (6)

$$R^s_{ONU_k} = \sum_{c=0}^{3} R^s_{c,k}.$$  \hspace{1cm} (7)

When $R < B_{min}$, the OLT decides $G_{s,k} = R^s_{c,k}$ and $G_k = R^s_{ONU_k}$, where $G_{s,k}$ is the granted bandwidth to CoS$_s$ of ONU$_k$. Then these results will be inputted to the PMB-DBA algorithm, so that the OLT can get the sub-carriers allocation results and the cycle time $T_c$. If $R$ is less than $T_{min}$, we let $T_c = T_{min}$.

When $R \geq B_{min}$, the bandwidth will be assigned to three CoSs by three steps.

Step 1: We need to meet the demand of CoS$_0$ first, i.e., $G_{0,k} = R^s_{c,k}$. The rest bandwidth that can be assign to CoS$_1$ and CoS$_2$ is formulated as follows:

$$B_{rest} = B_{max} - \sum_{k=1}^{K} G_{0,k}.$$  \hspace{1cm} (8)

To assign the rest bandwidth more reasonably, the limit of CoS$_1$, $W_{c} = \frac{W_k}{\sum_{c=1}^{K} W_k}$, (c=1,2 here) is shown as:

$$B^c_{lim} = B_{rest} \times W_c,$$  \hspace{1cm} (9)

where $W_c$ represents the different weights of CoS$_1$ and CoS$_2$. The total bandwidth requirement of CoS$_c$ is $B_{CoS_c} = \sum_{k=1}^{K} R^s_{c,k}$.

Step 2: When $B_{CoS_c} \leq B^c_{lim}$, we meet all the demand of CoS$_1$ as $G_{1,k} = R^s_{c,k}$. When $B_{CoS_c} > B^c_{lim}$, the different weights of SLAs, $W_c$, should be taken as the additional consideration with

$$B^c_{lim} = B_{rest} \times \sum_{c=1}^{K} W_c N_c,$$  \hspace{1cm} (10)

where $B^c_{lim}$ is the bandwidth limit of SLA$_c$ in CoS$_c$, and $N_c$ is the number of ONUs with SLA$_c$. In accordance of the limit, we can assign the bandwidth of CoS$_1$ by MAM to ensure higher level ONUs have more granted bandwidth. The term $G^m_{1,k}$ represents the $m$th stage allocation result of ONU$_k$ with CoS$_1$, so the first stage is

$$G^1_{1,k} = \min(R^s_{c,k}, B^c_{lim}).$$  \hspace{1cm} (11)

After the first stage allocation, we need to be aware of the extra bandwidth of CoS$_2$, $B^2_{ext}$. The 2nd stage allocation result is calculated as follows:

$$B^2_{ext} = \sum_{s=1}^{3} R^s_{1,k} - \sum_{k=1}^{K} G^1_{1,k}.$$  \hspace{1cm} (12)

$$G^2_{1,k} = \min \left( R^s_{1,k} - G^1_{1,k}, W_s \times \frac{W_k}{\sum_{c=1}^{K} W_c N_c^{s,plus}} \right)$$  \hspace{1cm} (13)

where $N^{s,plus}_c$ is the surplus number of ONUs having data of CoS$_s$ to transmit. Eq. (13) updates the surplus CoS$_s$ status of ONU$_k$ and the bandwidth limit of SLA$_c$ in CoS$_s$. The procedure is then iteratively repeated to nth stage until the $B^1_{lim}$ is fully allocated. So

$$G^1_{1,k} = \sum_{m=1}^{M} G^m_{1,k}$$  \hspace{1cm} (14)

where $G^1_{1,k}$ is the granted CoS$_1$ bandwidth to ONU$_k$.

Step 3: For the requested CoS$_2$ bandwidth, the allocation will be executed only once according to the limit as follows:

$$G^2_{2,k} = \min(R^s_{2,k}, B^2_{lim})$$  \hspace{1cm} (15)

where $G^2_{2,k}$ is the granted CoS$_2$ bandwidth to ONU$_k$. Finally, we can get the $G_k$ which represents the granted data size to ONU$_k$. It is defined as:

$$G_k = \sum_{c=0}^{3} G_{c,k}.$$  \hspace{1cm} (16)

Then the OLT inputs these results to the PMB-DBA algorithm. It
should be mentioned that the \( T_c \) may exceed the \( T_{\text{max}} \) when too much data be transmitted. In this case, the data traffic which is going to map in the time window between \( T_{\text{max}} \) and \( T_c \) (a slight amount of data is in this window and most of the data belongs to the lowest priority CoS) will not be transmitted in this cycle. The results of ORB-DBA algorithm need to be updated.

For the case that the number of transmitters exceeds the limit, ONUs will transmit data in sub-cycles and we define \( R_{\text{clq}} \) \((q = 1, 2, \ldots, Q)\) as the total bandwidth requirement of ONUs in the qth sub-cycle. An ICG will be inserted between two sub-cycles. The minimum and maximum time length of sub-cycle \( q \) can be expressed as \( T^{\text{min}}_{\text{clq}} \) and \( T^{\text{max}}_{\text{clq}} \).

\[
T^{\text{min}}_{\text{clq}} = (T_{\text{min}} - (Q - 1)T_{\text{IFG}}) \times \frac{R_{\text{clq}}}{\sum_{q=1}^{Q} R_{\text{clq}}} \tag{17}
\]

\[
T^{\text{max}}_{\text{clq}} = (T_{\text{max}} - (Q - 1)T_{\text{IFG}}) \times \frac{R_{\text{clq}}}{\sum_{q=1}^{Q} R_{\text{clq}}} \tag{18}
\]

In this case, the PMB-DBA algorithm will be implemented for each sub-cycle. The \( T^{\text{min}}_{\text{clq}} \) and \( T^{\text{max}}_{\text{clq}} \) of each sub-cycle are determined as \( T^{\text{min}}_{\text{clq}} = T^{\text{clq}}_{\text{min}} \) and \( T^{\text{max}}_{\text{clq}} = T^{\text{clq}}_{\text{max}} \).

4. Performance evaluation

To evaluate the performance of the proposed DBA scheme, we set up an OFDMA-PON simulation model containing 1024 sub-carriers. The modulation formats considered range from 8-QAM to 64-QAM. The total upstream data capacity is 15 Gb/s. Just for the purpose of evaluating the proposed PMB-DBA scheme, coherent detection is adopted. Let \( T_{\text{IFG}} = 1.7 \mu s \), \( T_{\text{IFG}} = 3 \mu s \), \( T_f = 8 \mu s \), \( T_{\text{min}} = 80 \mu s \), \( T_{\text{max}} = 2 \text{ ms} \), and the sampling rate of ADC/DAC be 4 GS/s. The synthetic network traffic is based on Poisson distribution in the simulation model. In addition, except where otherwise stated, the number of ONUs and the transmitters limit are set to 32 and 16 respectively [14].

Fig. 4 shows the overall throughput of proposed scheme, NEC scheme and TDM scheme. In the TDM scheme, one or more OFDMA frames, which are contiguous in time, are occupied by a single ONU. The MAC layer bursts can be directly mapped across all sub-carriers and EPON MAC layer can be combined with the OFDMA-PON physical layer without modification. However, it will cause the waste of bandwidth in the last allocated frame of an individual ONU. The mode of ONUs mapping with time order will cause many times of lasers switching, so that the IFGs are introduced [11]. The NEC scheme, which is proposed in [9], can further reduce the bandwidth waste relative to the TDM scheme. In this scheme, transmitters can share frames in frequency to eliminate the bandwidth waste in frames occupied between different ONUs, but IFGs still exist. Simulation results demonstrate that throughput of three schemes perform similar when the network offered load is greater than 0.9.}

\[
\text{network throughput (Gbps)}
\]

\[
\text{number of ONUs}
\]

\[
\text{average overhead in a cycle (%)}
\]

\[
\text{ONU offered load}
\]

\[
\text{end-to-end packet delay (ms)}
\]

\[
\text{proposed scheme CoS0}
\]

\[
\text{proposed scheme CoS1}
\]

\[
\text{proposed scheme CoS2}
\]

\[
\text{status based scheme CoS0}
\]

\[
\text{status based scheme CoS1}
\]

\[
\text{status based scheme CoS2}
\]
scheme in terms of the average end-to-end packet delay. It is obvious that the two schemes can guarantee reasonable delay of CoS0. The proposed scheme has a better performance when load > 0.4 for the following reasons. Firstly, the proposed PMB-DBA algorithm in the proposed scheme provides higher throughput for OFDMA-PON system. Secondly, the full-range ORB-DBA algorithm ensures that the bandwidth resource would not be squeezed by too much low-priority data. Thirdly, the parallel transmission characteristic of ONUs data in proposed PMB-DBA algorithm can ensure all the CoS0 data be transmitted in advance.

For the performance of CoS1, in advantage of the high bandwidth utilization, the proposed scheme is better than the status based scheme under high load condition. The performance of proposed scheme in CoS2 becomes worse as the load increasing because the MAM in proposed ORB-DBA algorithm restrains the excessive transmission of CoS2. Fig. 7 compares the maximum packet delay of these two schemes. It is obvious that the proposed algorithm can optimize the jitter performance of CoS0 and CoS1. Because in any network load condition, the full-range algorithm in the ORB-DBA algorithm can ensure the global QoS by preventing lower priority CoS from occupying overmuch bandwidth. Meanwhile, the higher overall throughput ensures better performance of proposed algorithm under the heavy load condition. Without the MAM, the performance of proposed algorithm is similar with status based algorithm for CoS2. In the full-range ORB-DBA algorithm, we also ensure that the data from higher SLA ONUs have better transmission performance. So in Fig. 8, simulation results demonstrate that the proposed algorithm effectively reaches lower packet loss rate of higher priority CoS from higher SLA ONUs.

5. Conclusions

A new MAC DBA scheme which includes a PMB-DBA algorithm and an ORB-DBA algorithm has been proposed in this paper. The proposed PMB-DBA algorithm can eliminate the effect of IFCs and ensure the equity of ONUs in consideration of the frame structure of OFDMA-PON. In order to further improve the bandwidth utilization, we have proposed a MBW-DSA algorithm which provides an optimal sub-carriers allocation solution for the physical mapping process. This ORB-DBA algorithm provides full-range optimization with SLA and CoS in any load condition. The MAM can strictly ensure lower packet delay and better jitter performance of higher priority CoS from higher SLA ONUs. These two algorithms are closely related and can improve the performance of the OFDMA-PON system together. Numerical simulations have indicated that the new MAC DBA scheme can ensure high system throughput and enhance the global QoS of the system.

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References