A Joint physical layer and MAC layer Bandwidth Allocation Scheme in Optical Access Network

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***Abstract*—To address the problem of mismatch between physical layer technology and MAC layer technology, we propose a joint physical layer and MAC layer bandwidth allocation scheme. Simulation results imply the optical system capacity be improved.**

Keywords—passive optical networks; physical layer; MAC layer; dynamic bandwidth allocation; fairness;

I. INTRODUCTION

With the dramatic bandwidth increase in backbone networks and speed growth in local-area networks, the bottleneck of access networks has become the growing gulf in between [1]. Passive optical networks (PONs) have been considered by many as an effective solution for "first mile" access networks. Dynamic bandwidth allocation (DBA) is one of the key technologies for PON systems, which can be allocated according to the real-time traffic requirements of optical network units (ONUs) to ensure the effective use of bandwidth [2].

In 2002, the classic DBA scheme, called interleaved polling with adaptive cycle time (IPACT), was first proposed in [3] where the next ONU uses the staggered polling method to poll before the previous ONU transmits. After that, the researchers have successively proposed many improved DBA based on IPACT, including: IPACT with grant estimation (IPACT-GE) scheme [1], sleep-based DBA (SB-DBA) [4], a DBA scheme with cost and performance consideration [5], Time-Aware DBA (TA-DBA) [6] and a variety of DBA schemes [7-9] that can be applied to 5G scenarios, etc.

Channel capacity is a key performance indicator of the PON system. In traditional optical access network technology, the physical layer data transmission and the MAC layer network management are mutually independent functions. Although the different locations and different environments of the ONUs will cause the physical layer channel quality of each ONU to be different, the traditional optical access networks adopt a fixed and unified link transmission rate for all ONUs. As a result, the link transmission rate will be determined by the ONU with the worst channel quality. With the development of physical layer technologies, the traditional single-rate optical signal transmission mode is being replaced by more complex and variable software defined forms. ONUs with good channel quality can select a higher channel transmission rate, while ONUs with poor channel quality can select a lower channel transmission rate to ensure data transmission quality, thus helping to improve the overall channel capacity and system performance.

Unlike the traditional DBA scheme which is independent on the physical layer, this paper proposes a new joint physical layer and MAC layer bandwidth allocation (JPM-BA) scheme. In the new bandwidth allocation scheme, not only the transmission bandwidth and time slot should be allocated for each ONU according to the traditional scheme, but also the ONU's key physical layer parameters including modulation rate and link transmission speed are determined considering the different channel qualities of ONUs. The paper is organized as follows: section II introduces the system architecture and model, section III introduces the proposed JPM-BA scheme, section IV is the simulation results and analysis, and the last section summarizes the paper.

II. OVERVIEW OF THE SYSTEM

In order to improve the capacity of the PON systems, it is assumed in this paper that an optical transceiver with a large-bandwidth is adopted in the OLT terminal to support a higher transmission rate. At the same time, digital subcarrier modulation technology [10,11] is used to divide the optical transceiver bandwidth of the OLT into eight channels. Each ONU only needs to use a low-cost narrow bandwidth optical transceiver to work on the allocated channel.

In a PON system, there are two main factors in the physical layer that cause different signal transmission quality among different ONUs:

(1) Insertion loss

The insertion loss introduced by the optical separator is the most critical factor of ODN attenuation. The different fiber links from the OLT to different ONUs result in different link insertion loss for different ONU with varying working environment and working state of the live connector. This is the key factor affecting the link transmission rate that one ONU could choose.

(2) Channel response

The channel response of the optical transceiver used in the OLT with wide bandwidth might not be an ideal constant over different channels. Compared with channels in the middle of the transceiver, the edge channel usually has an inferior channel response. For an ONU with a certain insertion loss in the fiber link, different channel allocation result can further affect the signal-to-noise ratio (SNR) of the transmitted signal and determine the highest link transmission rate that the ONU could use.

Different from a traditional time division multiplexed PON (TDM-PON) system with the same fixed link transmission rate for all ONUs, our system allows to assign different link transmission rates for different ONUs according to their channel qualities. For this purpose, software defined optical transceivers with flexible modulation formats and error correction coding redundancy can be used to adjust the link transmission rate. Compared with the scheme with fixed link transmission rate, the channel quality-based bandwidth allocation scheme will effectively increase the link transmission rate of different ONUs, thus reducing the size of the distribution time slot and increasing the overall transmission capacity of the system.

However, due to different insertion loss and channel response for different ONUs, different channel allocation results result in different link transmission rates for different ONUs. In order to achieve better system performance, a joint physical layer and MAC layer bandwidth allocation (JPM-BA) scheme for both channel and time slot allocation should be used. The mathematical model for optimising channel and time slot allocation in bandwidth allocation is presented and introduced in the following.

TABLE I. SYMBOLS AND MEANINGS

Symbol	Meaning
T_{DBA}	DBA period
N	Number of ONUs
N_c	Number of channels
BT_i	Basic bandwidth of *i*th ONU
α_i	Weight coefficient of *i*th ONU
$Loss_i$	Insertion loss of *i*th ONU
$Resp_j$	Channel response of *j*th channel
$buffer_i$	Current data length of *i*th ONU
L_i	Required bandwidth of *i*th ONU
B_i	Allocated bandwidth of *i*th ONU
$V_{i,j}$	Link rate of *i*th ONU on *j*th channel
$T_{i,j}$	Basic time slot of *i*th ONU on *j*th channel
T_j	The remaining time slot on *j*th channel
$\mathbf{S_j}$	The ONU set on *j*th channel

Suppose that different ONUs can have different service requirement, in order for the OLT to provide different service to different ONUs, a weight coefficient α_i for the *i*th ONU is defined as:

$$\alpha_i = BT_i \Big/ \sum_{i=1}^{N} BT_i \tag{1}$$

where (BT_i) is the bandwidth load requirement for the *i*th ONU. The higher the weight coefficient of the ONU, the more bandwidth the ONU can be assigned in the following dynamic bandwidth assignment process.

Under the assumption that ONU link loss and channel responses are known, the link transmission rate $V_{i,j}$ can then be obtained if the *i*th ONU is allocated to the *j*th channel. To meet the ONU's basic bandwidth load requirements (BT_i), it is easy to calculate the basic time slot size $(T_{i,j})$ of the *i*th ONU allocation on the *j*th channel with link transmission rate $V_{i,j}$ as in (2):

$$T_{i,j} = \begin{Bmatrix} BT_i \times T_{DBA} / V_{i,j}, i \in \mathbf{S_j} \\ 0, i \notin \mathbf{S_j} \end{Bmatrix} \tag{2}$$

Meanwhile, in order to avoid the high transmission delay and frame resequencing problems caused by ONU transmission on multiple channels, it is assumed that the same ONU cannot be transmitted on two or more channels in this studied system as in (3):

$$\sum_{j=1}^{Nc} (T_{i,j} > 0) = 1 \tag{3}$$

And each channel can only transmit the data from at most one ONU. That is, the time slot allocated by the channel should not be greater than the DBA period, as in (4):

$$\sum_{i \in S_j} T_{i,j} \le T_{DBA} \tag{4}$$

The optimization target of the JPM-BA problem is to allocate an available channel, the corresponding link transmission rate and basic time slot size to each ONU under the above constraints so as to minimize the total number of time slots C required for bandwidth allocation, as in (5). In the case of a certain total bandwidth, more users can be accommodated in the future if fewer time slots are used for each ONU.

$$C = Min(\sum_{i=1}^{N} \sum_{j=1}^{Nc} T_{i,j}) \tag{5}$$

III. THE JPM-BA SCHEME DETAILS

In a real passive optical network, the traffic of the ONUs might fluctuate over time. In order to improve the performance of the optical access system as much as possible, the traditional DBA scheme tries to allocate the bandwidth for each ONU according to the current data cache status of the ONUs. For the joint physical layer and MAC layer bandwidth allocation (JPM-BA) scheme studied in this paper, in addition to allocating the time slot for each ONU, it also needs to allocate the channel simultaneously, and determine the link transmission rate of the ONU according to the channel insertion loss and the channel response. However, compared with the traditional DBA scheme, the JPM-BA scheme is more complex and may cause the ONUs to frequently switch between different channels for different allocation periods.

However, the channel insertion loss of the ONU is relatively stable with time. In this paper, the JPM-BA scheme is thus implemented by combining static channel allocation with dynamic time slot allocation.

First of all, when an ONU registers with the PON system, it completes the static channel allocation according to its physical layer characteristics. Both the channel and the link transmission rate are determined.

Secondly, each channel works in an independent way for data transmission. For the group of ONUs on one channel, the conventional dynamic bandwidth allocation based on the weight coefficient can then be used for time slot allocation for each ONU.

The combination of static channel allocation and dynamic time slot allocation can effectively reduce the computational complexity of the JPM-BA scheme, while taking into account the performance improvement from joint allocation. The static channel allocation algorithm and dynamic time slot allocation algorithm used are described in detail below.

A. First-level static channel allocation algorithm

First, the OLT calculates and determines the total bandwidth and the weight coefficient of each ONU according to BT_i. In this study, a static channel allocation with low implementation complexity is proposed for each ONU to be processed one by one.

At the start of the static channel allocation, all channels are assumed to be available with full bandwidth. For the first ONU, it will choose the channel with the highest channel response to obtain best signal quality. Together with its insertion loss, the SNR can be computed for the ONU on its chosen channel to determine its link transmission rate for following data sending. Suppose that the *j*th channel is assigned to the first ONU with its link transmission rate as $V_{i,j}$. Then, the ONU can compute how much time slot is required to transmit BT_i on that channel with the determined link transmission rate and this part of time slot or bandwidth will be removed from the channel's free bandwidth for following ONUs.

For the *i*th ONU, channels with free bandwidth will be tried in an order of channel response from high to low. If the *j*th channel is assigned to the *i*th ONU, the link transmission rate $(V_{i,j})$ can then be determined based on its signal's SNR. Then, the ONU can compute how much time slot is required to transmit BT_i on that channel with the determined link transmission rate. Suppose that T_j is the remaining time slot for the *j*th channel.

1) If the remaining time slot is sufficient to transmit the basic bandwidth of the *i*th ONU, as in (6).

$$T_j \times V_{i,j} \geq BT_i \times T_{DBA} \tag{6}$$

Then the *j*th channel can be allocated to the ONU as its working channel. At the same time, the link transmission rate is also determined after the *i*th ONU is added to $\mathbf{S_j}$. The remaining time slot of the *j*th channel (T_j) will be updated as in (7):

$$T_j = T_j - T_{DBA} \times BT_i / V_{i,j} \tag{7}$$

2) Otherwise, if the *j*th channel does not have enough free time slot for the *i*th ONU to transmit its BT_i on the channel, the next channel will be tried for the static channel allocation.

If an ONU tries all channels and still cannot find enough bandwidth to meet its basic bandwidth requirement, it means that the current system can not support all ONUs. In order to satisfy the fairness of ONU and ensure that all ONUs can complete the static channel allocation, the basic bandwidth should be reduced in a proportional way for all ONUs to try the static channel assignment again.

If there exist multiple channels with the same channel response and all these channels have ONUs allocated from the static channel assignment, the ONUs can be re-assigned in a more balanced way without link transmission rate affected for these ONUs. A more balanced channel allocation can help to achieve a better performance for following dynamic bandwidth allocation.

The first-level static channel allocation algorithm uses as few time slots as possible to satisfy the basic bandwidth of all ONUs to complete the channel allocation. In the process of ONU allocation to the channel, if the basic bandwidth of the ONU is greater than the tolerable bandwidth of the channel, the basic bandwidth of each ONU is reduced together to ensure that each ONU can receive a fair bandwidth allocation.

TABLE II. FIRST-LEVEL STATIC CHANNEL ALLOCATION ALGORITHM

1:initialize BT_i , $Loss_i$ of ONU_i , $Resp_j$ of channels, *i*=1,2,...,*N*, *j*=1,2,... N_C .
2: calculate α_i according to (1), *i*=1,2...*N*
3: sort *i*th ONU in a certain order, for *i*=1...*N*, do
4: sort *j*th channel in ascending order of $Resp_j$,for *j*=1... N_C , do
5: allocate the static bandwidth to the *i*th ONU and calculate $V_{i,j}$ according to SNR.
6: if satisfy (6), then
7: { $\mathbf{S_j} = \mathbf{S_j} \cup i$,
8: update T_j ,
9: Break, }
10: end if
11: end for
12 if $i \cap \mathbf{S_j} = \varnothing$, $\forall j \in 1,2,...,N_C$
13: { reduce BT_i and restart static channel allocation, }
14: end if
15: end for

B. Second-level dynamic bandwidth allocation algorithm

In order to meet the different bandwidth requirements from different ONUs, a coefficient (α_i) is defined earlier in this paper as the basis for bandwidth allocation. The larger the weight coefficient is, the higher the allocated bandwidth an ONU can obtain. Dynamic bandwidth allocation is performed independently on each channel with the set of ONUs allocated on that channel. Available time slot from the DBA period to transmit data is dynamically allocated to each ONU in the set according to the BT_i and α_i of ONUs. In this paper, the DBA period is assumed to be a constant value.

Suppose that the OLT knows the length of data $(buffer_i)$ waiting to be sent by each ONU through REQUEST frames before dynamic bandwidth allocation is started each time, the bandwidth required for one ONU can then be computed as in (8):

$$L_i = buffer_i / T_{DBA} \tag{8}$$

In dynamic bandwidth allocation, multiple iterations are performed to complete the bandwidth allocation with reference to the α_i. In each iteration, the remaining free bandwidth (B_{free}) from the channel and the total weight coefficients (α_{excess}) of the ONUs that have not completed bandwidth allocation are calculated. Then, one ONU waiting for further bandwidth allocation will obtain part of bandwidth from the remaining bandwidth according to the ratio of the weight coefficients as in (9):

$$B_i = BT_i + B_{free} \times \alpha_i / \alpha_{excess} \qquad (9)$$

If the above updated B_i meets the ONU's bandwidth requirement for its data transmission, the bandwidth allocation ends for this ONU and the finalized bandwidth allocation is then $B_i = L_i$. However, if the above updated bandwidth is still not yet enough for the ONU as it required, then this ONU only gets the currently allocated bandwidth in this iteration. At the end of the current iteration, if there is free bandwidth not assigned yet in the channel, the ONUs that have not completed the bandwidth allocation can continue with the next iteration in order to obtain more bandwidth for data transmission from the remaining free bandwidth.

IV. SIMULATION RESULTS AND THE ANALYSIS

In this paper, the performance of the JPM-BA scheme is verified and analyzed using numerical simulation, programmed using MATLAB platform. The simulation contains 1 OLT, 256 ONUs, and 8 adjacent channels. For the physical layer variability among ONU's, the channel insertion loss of each ONU is randomly generated in the simulation and obeys a Gaussian random distribution model with average insertion loss set to be 20 dB and variance set to be 3 dB. However, a minimum insertion loss of 10 dB and a maximum insertion loss of 30 dB are assumed respectively.

At the same time, the channel response of the eight available channels is set to (-10, -3, -1, 0, 0 -1, -3, -10) dB from left to right. Under the same channel insertion loss, the ONU allocated to the edge channel with worse channel response may have 10 dB worse SNR when compared to ONU's allocated to the middle channel with better channel response. Further considering the different channel insertion loss, the difference in signal SNR in the system can be up to 30 dB at most.

The bandwidth of each channel is assumed to be 8 GHz in the simulation, and the magnitude of the channel response and the insertion loss are combined to calculate the SNR. For ONUs with lowest insertion loss and best channel response, the highest link rate is 96 Gbps in the simulation. On the other hand, the lowest link rate is 4 Gbps for ONUs with highest insertion loss and worst channel response. For other cases, the link rate is computed following the channel capacity formula for AWGN channel.

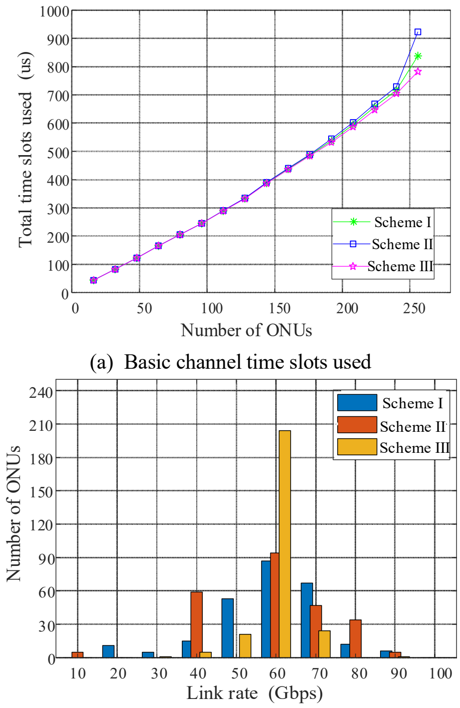
A. *Simulation of Static Channel Allocation Algorithm*

Static channel allocation is one of the cores of the JPM-BA scheme. The channel allocation is completed with the transmission link rate determined for ONU's during its registration phase. Due to the physical layer variability of each ONU, different channel allocation results in different performance and the ONU's were assigned with different link transmission rates. A comparison of the static channel allocation results using three different ONU ordering schemes is given in Figure 1, which are:

Scheme I: random sorting;

Scheme II: insertion loss sorted from low to high;

Scheme III: insertion loss sorted from high to low.



(b) Link rate distribution

Fig. 1. Static channel allocation results for the three schemes

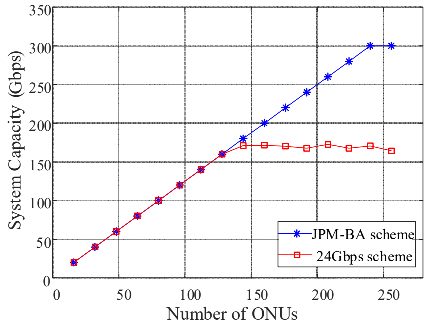
Figure 1(a) shows that when the system works at low load with small number of online ONUs, the three different static channel allocation schemes with different ONU order give similar performance because the system resources are sufficient to support the bandwidth demand of all online ONUs. However, as the number of online ONUs increases, the total required bandwidth increases accordingly. Compared with other schemes, the static channel allocation algorithm with ordering from high to low on the insertion loss, requires the least number of total time slots to be allocated and has the best performance at high load. Analysis shows that this scheme assigns ONUs with high insertion loss on channels with good channel response and ONUs with low insertion loss on channels with poor channel response. As a result, the link transmission rates are distributed more evenly and low link transmission rates are avoided. On the contrary, in scheme II, the ONUs with high insertion loss are supported with worse channels left. Due to the low link transmission rate available, it has to occupy a large number of time slots in the edge channel, resulting in a reduction of the total transmission capacity.

Figure 1(b) gives the comparison of the link rate distribution of the static allocation results from the three schemes. It can be seen that the ONU link rates are more concentrated around [50, 60] Gbps for scheme III while the ONU link rates are more dispersed for scheme I and scheme II, including five ONU's with link rates below 10 Gbps. These low-rate ONU's are the reason to seriously deteriorate the system performance.

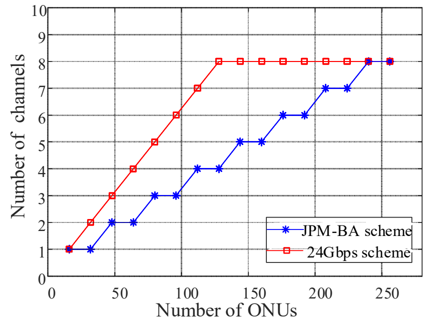
In the following, the traditional DBA scheme where all ONUs have the same link transmission rate is compared with the JPM-BA scheme. Therefore, the link transmission rate must be chosen to satisfy the requirements of the ONU with the worst SNR. Based on the previous Gaussian random distribution of link insertion loss and channel response model, the simulated link transmission rate that can be used by 256 ONUs simultaneously is approximately 24 Gbps.

Figure 2(a) compares the performance of the proposed JPM-BA scheme and the traditional scheme with 24 Gbps fixed link transmission rate for system capacity with increasing load. The larger the total bandwidth that the OLT can allocate to the ONUs, the greater the capacity the system can achieve. Obviously, the JPM-BA scheme can achieve significantly higher system capacity than the traditional scheme with fixed link transmission rate.

Meanwhile, Figure 2(b) shows the number of channels required for channel allocation under the two different schemes with different traffic loads. As the number of online ONUs increases, the number of occupied channels also increases. It is clear that at low system load, the JPM-BA scheme uses fewer channels than the traditional scheme with fixed link transmission rate, corresponding to lower power consumption. When the system is under high load, both schemes use the same number of channels, but the JPM-BA scheme can support more ONUs simultaneously.



(a) System capacity



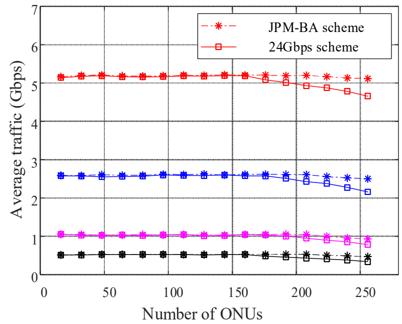
(b) Number of channels

Fig. 2. Comparison the JPM-BA scheme with the traditional 24Gbps scheme

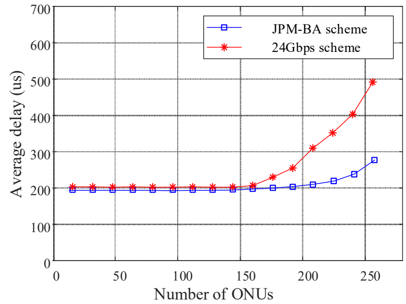
B. *Comparison of performance with the traditional scheme with 24Gbps fixed transmission rate*

In this part, both the static channel allocation and dynamic time slot allocation are included in the JPM-BA scheme to study its performance. The simulation process includes service generation from the ONU, channel and time slot allocation for the ONU by the OLT, and packet transmission for the ONU. The results of the simulation are recorded for statistical computation on packet delay and loss rate performance.

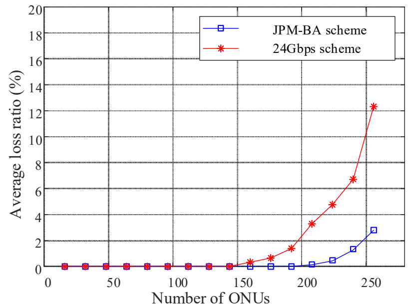
In the simulations, four types of ONUs with different traffic load are assumed. The requested basic bandwidth ratio of 10:5:2:1 is used. As the number of ONUs increases, the traffic load of the system increases with the ONU sending traffic. The average sending traffic is computed as the load that was sent to the channel by the ONU during its allocated time slot. In Figure 3(a), the four curves from top to bottom correspond to ONUs with traffic ratios of 10, 5, 2 and 1 respectively.



(a) Average sending traffic of ONU



(b) Average delay of ONU



(c) Average packet loss ratio of ONU

Fig. 3. Comparison of the overall performance of the two schemes

The JPM-BA scheme can obtain a larger system capacity and therefore can support a larger load and has better performance. As shown in Figure 3, the JPM-BA scheme has better performance than the traditional scheme with 24Gbps fixed transmission rate in terms of transmit traffic, delay and packet loss ratio performance metrics. The proposed JPM-BA scheme also supports fairness and quality of service for ONUs with different weight coefficients.

V. CONCLUSION

This paper proposes a new joint physical layer and MAC layer bandwidth allocation (JPM-BA) scheme to address the problem of insufficient capacity of traditional optical access networks using single rate optical signal transmission. Based on the insertion loss and channel response of ONUs from the physical layer, the JPM-BA scheme allocates different link rates for different ONUs with different signal transmission quality to increase the overall capacity of the system. Meanwhile, in order to reduce the high computational complexity of the JPM-BA scheme, a combination of static channel allocation and dynamic bandwidth allocation is proposed. Firstly, when an ONU registers to become online, the static channel allocation is used with one working channel allocated to the ONU together with its link transmission rate. Secondly, during data transmission, dynamic bandwidth allocation is used to allocate transmission time slots for ONUs according to the buffer size of saved data. Simulation results confirm that the proposed JPM-BA scheme can effectively increase the system capacity compared to the traditional DBA scheme with fixed transmission rate. The proposed JPM-BA scheme also shows significant improvement in transmission traffic, packet delay and packet loss ratio performance compared with the traditional scheme.

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