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A Novel Robust and Efficient Dynamic Bandwidth Allocation Scheme Over a Long-Reach Passive Optical Network

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***Abstract*—Long-Reach passive optical networks (LR-PONs) have been considered to be promising solutions for future access networks. In this paper, we proposed a decentralized medium access control (MAC) scheme over an LR-PON network architecture which provides direct inter-ONU communication through an (N+1)×(N+1) star coupler. In the proposed MAC scheme, a profit-weight-based-plus dynamic bandwidth allocation (P-DBA$^+$) scheme is presented. P-DBA$^+$ is a novel excess bandwidth distribution scheme with quality of service (QoS) provisioning. Simulation results indicate that the scheme attains exceptional system performance under various traffic loads and burstiness, providing fair, efficient and robust scheduling, and ensures the QoS requirements.**

Keywords—Long-Reach Passive Optical Network (LR-PON), Medium Access Control (MAC), Dynamic Bandwidth Allocation (DBA), Quality of Service (QoS).

I. INTRODUCTION

Over the past decade, a massive increase in broadband access applications has led to new access network architectures, such as Long-Reach PONs (LR-PONs) [1, 2], which extend the span of the traditional PONs from 20 km to 100 km and beyond. Because of the extremely long propagation delays in LR-PONs, the centralized control schemes adopted in PONs for upstream bandwidth allocation give rises to drastic delay degradation. Some studies have addressed this problem by exploiting various network architectures to support direct inter-ONU communication, whereas other studies focus on the design of the medium access control (MAC) scheme. To attain robust and exceptional system performance, we focus on these two major concerns.

Existing MAC schemes, such as IPACT [3] and multi-thread polling [4], are based on the multipoint control protocol (MPCP), which exchanges control information between optical network units (ONUs) and the optical line terminal (OLT) to arbitrate the upstream transmission schedule. Although multi-thread pooling utilizes the idle time between two successive cycles of IPACT (thus improving throughput), the packet delay still relates to round-trip time (RTT), and deteriorates as the RTT increases.

Through a nearly deployed (N+1)×(N+1) star coupler (SC) [5], we have earlier proposed a decentralized MAC scheme by using in-band control over an LR-PON network architecture [6]. The MAC scheme is associated with an efficient and

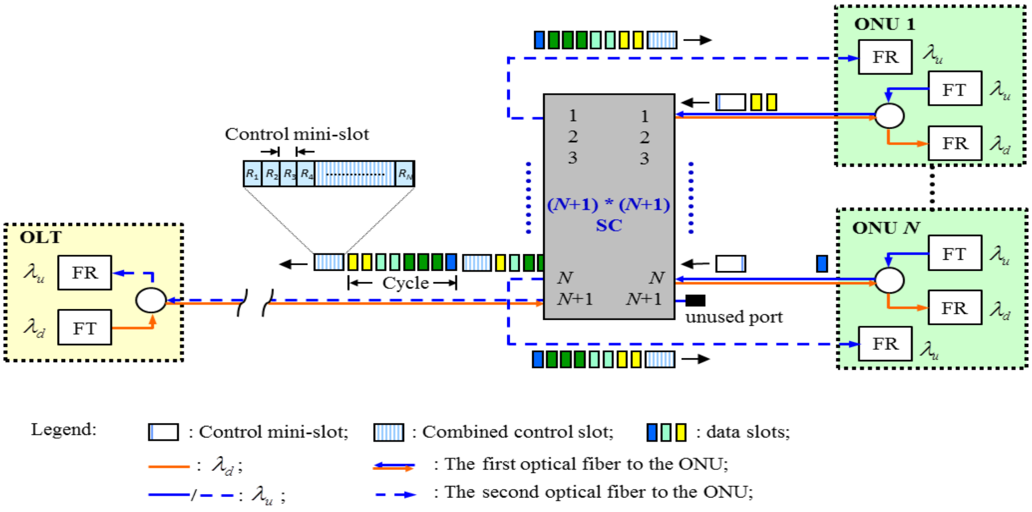


Fig. 1. The LR-PON network architecture based on a (N+1) * (N+1) passive star coupler; Cycle and control slot structures.

robust dynamic bandwidth allocation (denoted as P-DBA) scheme. P-DBA tackles the problem of the existing DBA schemes [7-9], which have allocated the excess bandwidth according to the queue status of each ONU (denoted as Q-DBA), resulting in unfairness and non-robustness when under attack by malevolent nodes [2]. In this paper, we further enhance the DBA scheme, called profit-weight-based-plus dynamic bandwidth allocation (P-DBA$^+$) scheme, to seamlessly integrate the best-effort and QoS traffic. While inheriting all the benefits from P-DBA, the P-DBA$^+$ scheme overwhelms the extremely long propagation delay in LR-PONs, enabling the upstream bandwidth to be fully utilized, providing fair and robust scheduling efficiently, and further meeting the QoS requirements.

II. NETWORK ARCHITECTURE

In the network architecture presented in Fig. 1, the OLT is connected to N number of ONUs (indexed from ONU 0 to ONU N-1) through a nearly deployed (N+1)×(N+1) SC. Each ONU uses two distribution fibers that are connected to the SC. The upstream traffic sent from ONUs is coupled at the SC and then routed to the OLT and all ONUs by using wavelength λ_u. The downstream traffic from the OLT is broadcasted to all ONUs by using wavelength λ_d. Thus, each ONU has two fixed-tuned receivers that receive the downstream traffic from the OLT and the redirected traffic from all ONUs. Moreover, each ONU has one fiber for downstream and upstream traffic, and a second fiber that delivers redirected traffic (all upstream traffic of ONUs that is coupled at the SC) back to the ONU. This design provides direct inter-ONU communication and enables control information to be received in a short time, regardless of the long propagation delay in LR-PONs, thereby facilitating the distributed MAC scheme.

III. DYNAMIC BANDWIDTH ALLOCATION SCHEME

As shown in Fig. 1, each ONU in the network architecture is assumed to be equally distanced from the SC, but it is easy to compensate the different distances among ONUs and the SC. For example, an ONU can simply add a short optical line or set a different timer to offset and synchronize among ONUs. These issues go beyond the scope of the paper. Each ONU concurrently fill its requirement (i.e., R_i, which is the number of requested slots reserved from ONU i) on its dedicated control minislot. Therefore, all control minislots of ONUs reach the SC at the same time, being coupled at the SC, and then broadcast to all ONUs and the OLT. Based on the same demand matrix, all ONUs execute the same distributed algorithm to transmit data at the next cycle time. By using the direct inter-ONU communication and in-band control in the LR-PON network, the packet delay is completely irrelevant to the extremely long propagation delays between the OLT and ONUs, thus yielding drastic delay performance improvements.

The weight-based DBA scheme is described as follows. Given a fixed maximum cycle time (i.e., T_{max} number of data slots) and N ONUs in the network, each ONU has an average share (or minimum guaranteed bandwidth), $B_{min} = T_{max} / N - T_{guard}$, to transmit data per cycle time, where T_{guard} is the guard time between two successive ONUs transmission. All ONUs are divided into two groups – lightloaded and highloaded – according to whether their requests exceed B_{min}. The lightloaded ONUs are allocated with whatever they require (R_i), whereas the highloaded ONUs receive an additional excess bandwidth (B_i^{excess}) as well as B_{min}. Most previously reported weight-based DBA schemes distribute the total excess bandwidth (B_{total}^{excess}) based on the requirements of ONUs (i.e., R_i, which are usually the queue lengths of ONUs). Such requirements-weight-based (or queue-weight-based) DBA scheme is denoted as Q-DBA in this paper. Specifically, the more an ONU requests, the more excess bandwidth it receives, which results in unfairness, particularly when under attack by malevolent nodes.

```
Profit_excess_DBA() //distribute excess bandwidth to all ONUs
1. $B_{total}^{excess} = \sum_{i=0}^{N-1} max(B_{min} - R_i, 0);$
2. for(each ONU i)
     if( $R_i > B_{min}$ ) //the set K contains all highloaded ONUs
      Add ONU i into set K; endif endfor
3. for(ONU $i \in K$ )
     $B_i^{excess} = B_{total}^{excess} \cdot profit_i / \sum_{j \in K} profit_j;$ endfor
Update_Profit_during_Cycle()
1. for(each ONU i)
     for (each new arrival in queue)
      if(priority(new arrival) == HIGH) $profit_i = profit_i + Hprofit$ ;
     for (each departure)
      if(priority(the departure) == HIGH) $profit_i = profit_i - Hprofit$ ;
```

```
Update_Profit_at_CycleEnd()
1. $raise = 0;$
2. for(each ONU i)
     $profit_i = profit_i - B_i^{excess}$; //update $profit_i$
    if( $profit_i < raise$) //set raise to the lowest negative $profit_i$
      $raise = profit_i$ ;
     endif
  endfor
3. if(raise <=0)
    for(each ONU i)
       $profit_i = profit_i + |raise| + 1$; //upgrade all $profit_i$ to $\geq 1$
    endfor
   endif
```

Fig. 2. Detailed P-DBA$^+$ algorithm.

In this paper, a novel profit-weight-based-plus DBA scheme (P-DBA$^+$) is proposed to allocate bandwidth among ONUs fairly and efficiently, and is further enhanced with QoS provision. The algorithm is detailed in Fig. 2. The traffic is separated into high priority data and low priority data. The high priority data has absolutely high priority over low priority data. That is, each ONU sends high priority data first, and then sends low priority data. At the cycle begins, the additional excess bandwidth is distributed based on the profit values of ONUs, which are derived from the usage of excess bandwidth of each ONU and together with the traffic amount of high priority data.

The profit value is derived as follows. First, the profit value is initially set to B_{min}. At the cycle end, the profit value is reduced by the amount of that the ONU receives its excess bandwidth. To satisfy QoS requirements, P-DBA$^+$ temporarily distribute more excess bandwidth to those ONUs which are with high priority traffic, thus profit value of the ONUs are also temporarily increased correspondingly. We then introduce another system parameter, *Hprofit*, which value can be optionally chosen based on the system configuration. During the cycle, $profit_i$ (i.e., the profit value of ONU *i*) increases the value of *Hprofit* at each high priority data arrival, and decreases the value of *Hprofit* at each high priority data departure. In other words, when an ONU has *x* number of high priority arrivals in a cycle, the profit values are increased as $profit_i = profit_i + x \cdot Hprofit$. When there is *y* number of high priority packets being transmitted, the *profit* value will be updated as $profit_i = profit_i - y \cdot Hprofit$. Therefore, when an ONU has a large amount of high priority data, the ONU may receive large amounts of excess bandwidth. To conduct fair bandwidth allocation, the temporarily high bandwidth distribution will be eliminated by decreasing the profit value when the high priority data has been already transmitted.

To clearly compare Q-DBA and P-DBA$^+$, we explain it via a simple example as shown in Fig. 3. The ONU *m* is a malicious ONU, so the numbers of new arrivals in each cycle are always much exceeding B_{min}. The ONU *p* and *q* are normal ONUs. The ONU *p* has bulk arrivals in the consecutive cycles (from cycle *K* to cycle *K*+2). And, the ONU *q* has arrivals more than B_{min} in cycle *K* but less than B_{min} in the following cycles (from cycle *K*+1 to cycle *K*+2).

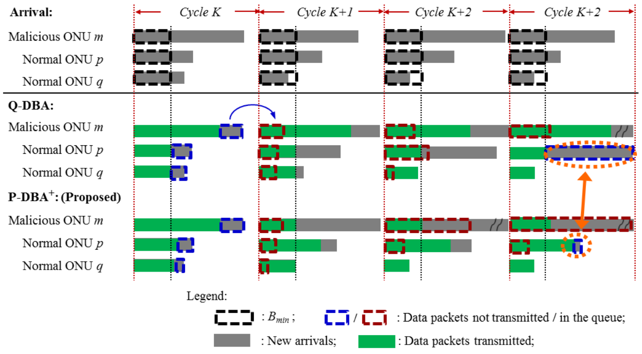


Fig. 3. Q-DBA and P-DBA$^+$ comparisons.

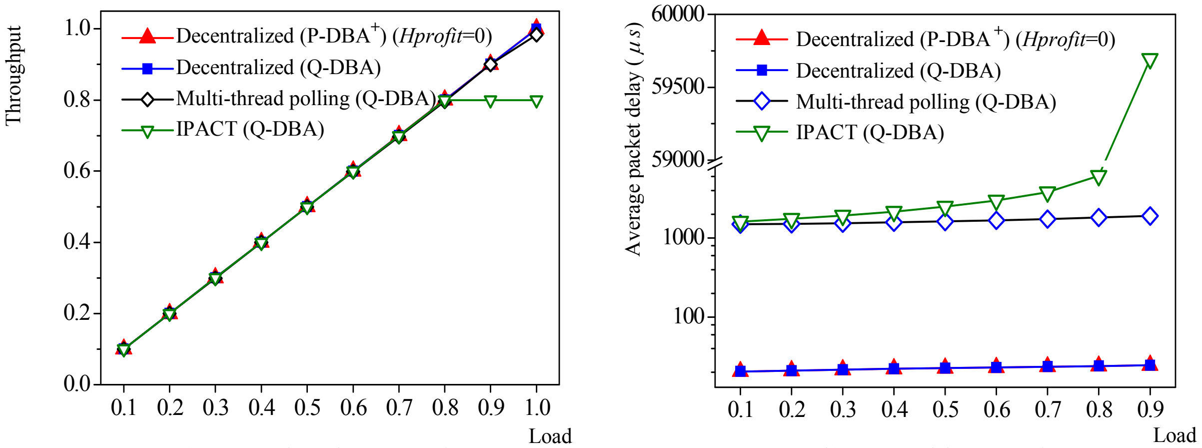
In Q-DBA, as shown in the figure, all the excess bandwidth is distributed to the malicious ONU *m*. The normal ONU *p* and ONU *q* are allowed to transmit at most B_{min} per cycle, thus the exceeding arrivals ($>B_{min}$) will wait in the queue. We observe that ONU *p* has buffered lots of data in its queue in cycle *K*+2, resulting in an increase in delay performance. The buffered packets will be fully consumed only when ONU *p* has fewer arrivals in the future cycles. Note that as the load is higher, the delay deteriorates. Therefore, Q-DBA is noticeably affected by malicious ONUs, and thus is not robust when under attack.

As shown in Fig. 3, we directly use a simple example to clearly describe P-DBA$^+$. In cycle *K*, we assume the malicious ONU *m* obtains most of the excess bandwidth, thus $B_m^{excess} \cong B_{total}^{excess}$. To be best explained, we further assume the malicious ONU *m* obtains $B_m^{excess} = k \cdot B_{min}$, where $k > 1.0$. Also, assume ONU *m* has initial $profit_m$ value as B_{min}. After this cycle, $profit_m$ is updated to be $profit_m = profit_{old\_m} - B_m^{excess} = (1-k) \cdot B_{\min}$, resulting in $profit_m < 0$. Note that the profit values must be set as positive values, so the ONUs are allowed to share the excess bandwidth reasonably based on the profit ratio, ($= profit_i / \sum_{i \in K} profit_i$). We observe that once one ONU sets its *profit* value to be 0, this ONU will obtain no excess bandwidth even if no other ONUs need extra bandwidth. Therefore, we raise the profit values to be at least 1.

In cycle *K*, since ONU *m* obtains the maximum excess bandwidth in this cycle, the updated $profit_m$ must be the minimum values among all profit values. Based on the algorithm, we obtain $raise = profit_m$, where $raise < 0$. After we add an amount ($|raise| + 1$) to all profit values, $profit_m$ is 1, whereas $profit_p$ and $profit_q$ are much greater than 1. Therefore, in the following cycles, the malicious ONU *m* obtains nearly none of the excess bandwidth, and thus transmits only around B_{min} of data. And the other normal ONUs obtain more excess bandwidth due to higher profit values, so the ONU *p* is allowed to have more excess bandwidth to transmit data from cycle *K*+1 to cycle *K*+2. Unlike Q-DBA, as shown in cycle *K*+2, the normal ONU *p* has very few data queued. Therefore, P-DBA$^+$ is not affected by malicious ONUs, and thus is fair and robust even when under attack.

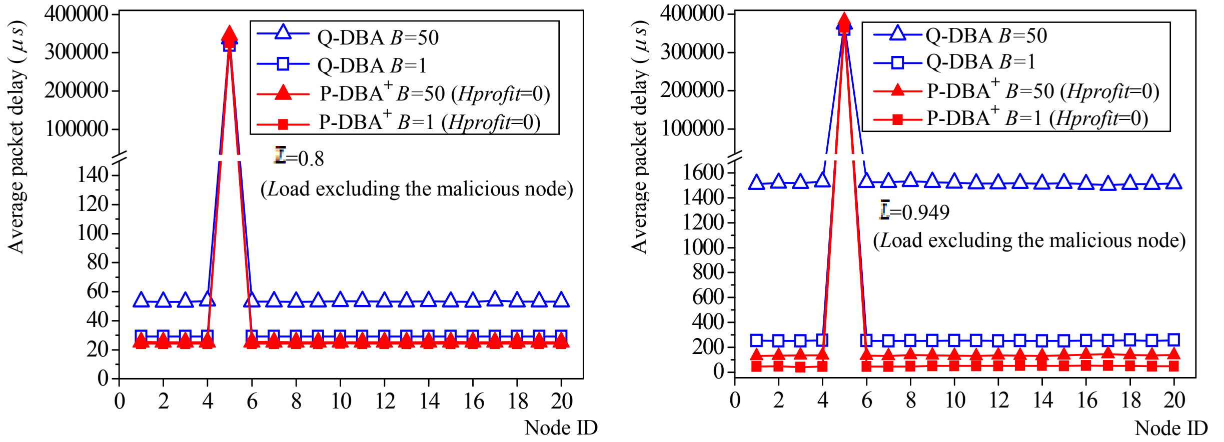
IV. SIMULATION RESULTS

In this section, we present simulation results to demonstrate the performance of the proposed scheme. A 100-km 10-Gb/s LR-PON consisting of an OLT and 20 ONUs (N = 20) is considered. Each ONU is with 1 km from the SC. Each cycle consists of 0.01 ms. Traffic is generated following a two-state (*H* and *L*) Markov modulated Poisson process (MMPP) conducted to model smooth and bursty traffic. Specifically, the MMPP is characterized by four parameters (α, β, λ_H, and λ_L), where α (β) is the probability of changing from state H (L) to L (H) in a slot, and λ_H(λ_L) represents the probability of arrivals at



(a) System throughput comparison

(b) Average delay comparison



(c) Delay comparisons under high load with malicious nodes

(d) Delay comparisons under saturated load with malicious nodes

Fig. 4. Throughput and delay performance comparisons.

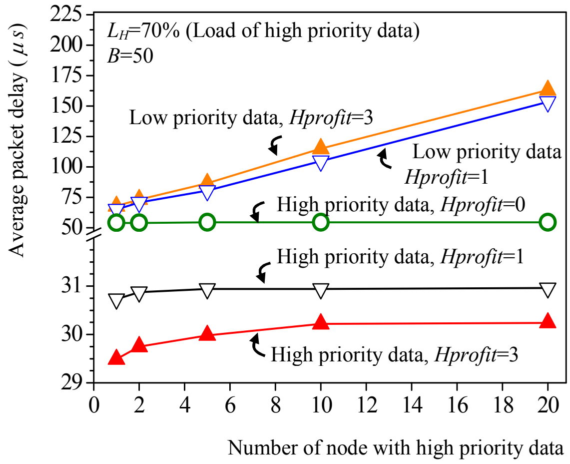


Fig. 5. Mean delay comparisons for high priority data and low priority data.

state H (L). Accordingly, given λ_L=0, the mean arrival rate can be expressed as $\beta\times\lambda_H/(\alpha+\beta)$, and traffic burstiness (B) can be given by $B=(\alpha+\beta)/\beta$. Finally, simulation is terminated after reaching a 95% confidence interval. The load (L) indicates the number of packets to be generated per time slot. The load ($\bar{L}$) denotes the system load excludes the malicious node, the traffic of which is set as 0.2. Note that the upper bound of $\bar{L}$ is 0.95 (=1-1/N).

Fig. 4 (a) and (b) illustrate comparisons of two centralized schemes (IPACT and multi-thread polling) and our proposed decentralized schemes. Q-DBA denotes the queue-weight-based DBA (where the weight is R_i), and P-DBA$^+$ denotes the proposed profit-weight-based-plus DBA. As depicted in the figure, multi-thread polling achieves excellent system throughput, resolving the idle time problems of IPACT; however, it still yields considerable delay degradation because of the long propagation time between the OLT and ONUs. The results indicate that the proposed decentralized algorithms exhibit a nearly three-order-of-magnitude improvement in delay performance compared with the centralized algorithms over LR-PONs. In Fig. 4(c), under high-loads and high-burstiness traffic, the proposed P-DBA$^+$ scheme is completely unaffected by the malicious node. By contrast, the Q-DBA scheme gives rise to delay deterioration (and thus unfairness) to the normal nodes. As the traffic burstiness and load ($\overline{L}$) increase, the delay increases as illustrated in Fig. 4(d). Consequently, the proposed P-DBA$^+$ scheme is evidently robust and fair, even when under attack by malevolent nodes.

Fig. 5 demonstrates the QoS differentiation performance. Both high priority and low priority traffic delay increases, as high priority traffic increases. The high priority traffic exhibits lower delay than low priority traffic, thereby attaining QoS provisioning. Moreover, by increasing the value of *HProfit*, the high priority traffic delay reduces at a negligible cost that the low priority traffic delay increases slightly.

To conclude, under P-DBA$^+$, the results indicate that the mean delay of the high priority data is about 29 to 55 μs under either normal condition or malicious-node-attack condition under various values of *HProfit*. In contrast, under Q-DBA, the mean delay of the high priority data is about 55 μs under normal condition, but exhibit extremely high delay ($\approx 1500\mu s$) when the network is attacked by malicious node(s) at high loads.

V. CONCLUSIONS

In this paper, we have presented a novel profit-weight-based-plus DBA (P-DBA$^+$) scheme over a LR-PON network architecture that provides direct inter-ONU communication through an (N+1)×(N+1) star coupler. By taking advantage of the rerouted in-band control signaling, the upstream transmission is scheduled by a distributed MAC scheme, thereby resolving the problem caused by the extremely long propagation delay in LR-PONs and enabling exceptional system performance to be attained. Moreover, the P-DBA$^+$ scheme efficiently distributes the excess bandwidth to the overloaded ONUs based on a profit value derived from the excess bandwidth used by each ONU and also based on a system parameter, *HProfit*. Specifically, the P-DBA$^+$ scheme can be applied on all various PON network architectures: the traditional PON networks, the LR-PON networks with an (N+1)×(N+1) star coupler, and the others. The P-DBA$^+$ scheme is demonstrated to ensure QoS and also be fair and robust even when under attack from malicious nodes.

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