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A high performance long-reach passive optical network with a novel excess bandwidth distribution scheme

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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 propose a distributed medium access control (MAC) scheme over an advantageous LR-PON network architecture that reroutes the control information from and back to all ONUs through an $(N+1) \times (N+1)$ star coupler (SC) deployed near the ONUs, thereby overwhelming the extremely long propagation delay problem in LR-PONs. In the network, the control slot is designed to contain all bandwidth requirements of all ONUs and is in-band time-division-multiplexed with a number of data slots within a cycle. In the proposed MAC scheme, a novel profit-weight-based dynamic bandwidth allocation (P-DBA) scheme is presented. The algorithm is designed to efficiently and fairly distribute the amount of excess bandwidth based on a profit value derived from the excess bandwidth usage of each ONU, which resolves the problems of previously reported DBA schemes that are either unfair or inefficient. The simulation results show that the proposed decentralized algorithms exhibit a nearly three-order-of-magnitude improvement in delay performance compared to the centralized algorithms over LR-PONs. Moreover, the newly proposed P-DBA scheme guarantees low delay performance and fairness even when under attack by the malevolent ONU irrespective of traffic loads and burstiness.

1. Introduction

The massive increase of broadband access applications, such as real-time network gaming, IPTV, backhauling of broadband wireless data, etc., has significantly contributed to the evolution of new access network architectures. The broadband optical access network, TDMA-based PON [1,2], has been considered the most attractive and low-cost access technology. TDMA-based PON is a multipoint-to-point tree-structure network. In the downstream transmission, the optical line terminal (OLT) simply broadcasts data to all optical network units (ONUs); while in the upstream direction, all ONUs share the same wavelength of TDMA PONs via a multipoint control protocol (MPCP) to avoid collisions and support bandwidth negotiation between the OLT and ONUs. Based on MPCP, the OLT collects all the bandwidth requirements of ONUs and uses a centralized medium access control (MAC) scheme to schedule and poll the ONUs for upstream transmission.

There are two prevailing centralized MAC schemes: IPACT [3,4] and multi-thread polling [5,6]. Based on MPCP, the control information is exchanged between ONUs and the OLT. In IPACT, the OLT schedules the upstream transmissions of all ONUs following a round-robin fashion. That is, the OLT polls one ONU after the other with only a small time gap between two successive ONU bursts, which constitutes a polling transmission cycle. To make a fair bandwidth allocation, the OLT executes the dynamic bandwidth allocation (DBA) scheme when it collects all ONUs' requirements (which are piggybacked to the transmitted data) in a transmission cycle. At that time, the OLT determines the transmission schedule, and then it polls the first ONU again to transmit the data for the next transmission cycle. From the time until the first ONU receives the GATE message, and the time from the ONU transmits data until the data reaches the OLT, there still has one round-trip time (RTT) idle time between two successive transmission cycles. Multi-thread polling scheme lifts the problem by inserting additional one or multiple threads to utilize the idle time between two successive transmission cycles of IPACT. Although multi-thread polling scheme improves the network throughput and delay performance, its packet delay is still proportional to RTT because of the negotiations between the OLT and ONUs via MPCP.

Over the past decade, the explosive demand for bandwidth has led to new access network architectures, such as Long-Reach PONs (LR-PONs) [2,7–12], which extend the span of the traditional PONs from 20 km to 100 km and beyond. Because of the long

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propagation delays in LR-PONs, the centralized control schemes adopted in traditional PONs for upstream transmission give rises to drastic delay degradation. To achieve high system performance, some studies have addressed this problem by exploiting various network architectures to support direct inter-ONU communication [13–18], which is to get rid of MPCP and thus facilitate a distributed MAC scheme, whereas other studies focus on the design of the MAC schemes [3–6] and DBA algorithms [19–22]. Note that a distributed MAC scheme indicates that each ONU receives the same control information (with all bandwidth requirements of all ONUs) and then each ONU executes the same distributed algorithm obtaining the same upstream (to OLT) and inter-ONU transmission scheduling. In this paper, to attain robust and exceptional system performance, we focus on these two major concerns.

We first survey the LR-PON network architectures with direct inter-ONU communication [13–18], which brings about two significant advantages. First, the network system enhances the system throughput by avoiding that the ONU to ONU traffic occupies both upstream and downstream bandwidth as in traditional PONs. Second, because the control information issued by ONUs will be rerouted back to all ONUs in a short delay, this network architecture facilitates a distributed MAC scheme. Existing LR-PON network architectures redirect the inter-ONU traffic to all ONUs by some passive optical components deployed near the ONUs side. In [15], it uses one Fiber Bragg grating (FBG) and one $1 \times N$ star coupler (SC), where the FBG is placed before the SC, static tuned to the wavelength for inter-ONU communication. The work in [16,17] use an $N \times N$ SC and place two FBGs inside each of the ONU to overcome the problem of the environment effects to FBG. The works [15–17] all incur a problem that the downstream and inter-ONU traffic uses the same downstream wavelength, the OLT and ONUs must all participate in the downstream scheduling decisions, which complicates the MAC algorithms. In [18], the OLT is connected to N number of ONUs via an $(N+1) \times (N+1)$ SC deployed near the ONUs. Each ONU has one fiber for both downstream and upstream traffic, and a second fiber that delivers upstream and inter-ONU traffic back to the ONU. When a distributed MAC scheme is adopted, such design has advantages over the network architectures presented in [15–17] because only ONUs participate in the distributed decisions for the upstream and inter-ONU transmission.

Another major goal is to develop an efficient and robust DBA algorithm. Among all the existing DBA schemes [3–12,19–22], excess bandwidth distribution within a given fixed cycle time has received the most attention [10]. Most of them allocate the excess bandwidth according to the demand of each ONU [3–6], (which is usually the queue length of each ONU). This DBA has been adopted in most of the previous studies, thus we refer it as Q-DBA, which indicates the queue-weight-based DBA or requirement-weight-based DBA. In Q-DBA, the more an ONU requests, the more excess bandwidth the ONU receives. If there exists malicious ONU(s) (which attempts to transmit overly large number of data trying to monopolize bandwidth), most or nearly all of the excess bandwidth will be distributed to them, thus undergoing the unfairness and non-robustness problems. Some studies have resolved this problem by proposing complex algorithms to enforce the fairness among ONUs [20–22]. In [20], it uses a system parameter (a degree of greediness ratio) and sliding window to distribute the excess bandwidth. This scheme is fair and robust, but it suffers from complex algorithms and is difficult to decide a proper system parameter to achieve the fairness of the ONUs. In [21], the scheme maintains an excess bandwidth credit pool for carrying excess bandwidth across cycles, and also supports unequal weight-based excess distribution. Although it is a fair scheme, it is difficult to find a correct decay parameter to decay the credit pool, and only simulation results are proposed to help decide the correct parameter settings under various system configurations. While in [22], it adopts an iterative procedure for allocating excess bandwidth, which is a high complexity algorithm focused on maintaining the fairness index to be 1.0. The goal of this paper is to propose a new DBA to provide fair and robust scheduling efficiently.

In this paper, we propose a novel excess bandwidth distribution scheme and demonstrate the performance of the proposed DBA scheme over an LR-PON network architecture, which provides direct inter-ONU communication through an $(N+1) \times (N+1)$ [18] SC. For upstream transmission, each control slot is designed to contain the bandwidth requirements of all ONUs and is in-band time-division-multiplexed with a number of data slots within a cycle. The control information sent from ONUs is coupled and re-routed back in a short delay through the SC, regardless of the long propagation delay in LR-PONs. This design facilitates a distributed medium access control (MAC) scheme, and thus overwhelms the extremely long propagation delay in LR-PONs and also enables the upstream bandwidth to be fully utilized. In the proposed MAC scheme, a profit-weight-based DBA scheme (referred as P-DBA in this paper) with a novel excess bandwidth distribution scheme is presented. The scheme is demonstrated to be fair and robust, particularly advantageous when under attack from malicious ONU(s). The algorithm is designed to efficiently and fairly distribute the amount of excess bandwidth based on a profit value derived from the excess bandwidth usage of each ONU, which resolves the problems of previously reported DBA schemes that are either unfair or inefficient. As demonstrated in the simulation results, our scheme attains exceptional high system performance under various traffic loads and burstiness, and more importantly, it provides fair, efficient and robust scheduling.

We summarize two major contributions in this paper as follows.

- We propose a new in-band control and data cycle structures over an LR-PON network architecture, which provides direct inter-ONU communication through an $(N+1) \times (N+1)$ SC. The control information directly coupled and re-routed back in a short delay, facilitating a distributed MAC and thus resolving the problem of the long propagation delay in LR-PONs via centralized MPCP. The inter-ONU communication network architecture also facilitates efficient bandwidth usage, while at the cost of using an $(N+1) \times (N+1)$ SC, and an extra fixed-tuned receiver and dual fibers for each ONU.
- We propose a novel dynamic bandwidth allocation scheme (P-DBA), which can be applied to both traditional PON architecture and the PON with any inter-ONU communication architecture. The P-DBA efficiently distributes excess bandwidth to the overloaded ONUs by a profit value which is derived from the excess bandwidth usage history of each ONU. Although the requirement-weight-based DBA (Q-DBA) has similar performance as P-DBA under normal traffic conditions, the P-DBA is demonstrated to be particularly advantageous when under attack from malicious ONU(s).

The remainder of this paper is organized as follows. In Section 2, we present the proposed in-band control and data cycle structures exploited in the LR-PON network architecture which provides direct inter-ONU communication through an $(N+1) \times (N+1)$ SC. In Section 3, we describe the proposed dynamic bandwidth allocation scheme and outline its detailed algorithm. In Section 4, we make performance comparisons between Q-DBA and P-DBA. Simulation results are then shown in Section 5. Finally, concluding remarks are given in Section 6.