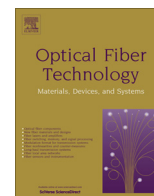




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# Network coding based joint signaling and dynamic bandwidth allocation scheme for inter optical network unit communication in passive optical networks



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## ABSTRACT

As an innovative and promising technology, network coding has been introduced to passive optical networks (PON) in recent years to support inter optical network unit (ONU) communication, yet the signaling process and dynamic bandwidth allocation (DBA) in PON with network coding (NC-PON) still need further study. Thus, we propose a joint signaling and DBA scheme for efficiently supporting differentiated services of inter ONU communication in NC-PON. In the proposed joint scheme, the signaling process lays the foundation to fulfill network coding in PON, and it can not only avoid the potential threat to downstream security in previous schemes but also be suitable for the proposed hybrid dynamic bandwidth allocation (HDBA) scheme. In HDBA, a DBA cycle is divided into two sub-cycles for applying different coding, scheduling and bandwidth allocation strategies to differentiated classes of services. Besides, as network traffic load varies, the entire upstream transmission window for all REPORT messages slides accordingly, leaving the transmission time of one or two sub-cycles to overlap with the bandwidth allocation calculation time at the optical line terminal (the OLT), so that the upstream idle time can be efficiently eliminated. Performance evaluation results validate that compared with the existing two DBA algorithms deployed in NC-PON, HDBA demonstrates the best quality of service (QoS) support in terms of delay for all classes of services, especially guarantees the end-to-end delay bound of high class services. Specifically, HDBA can eliminate queuing delay and scheduling delay of high class services, reduce those of lower class services by at least 20%, and reduce the average end-to-end delay of all services over 50%. Moreover, HDBA also achieves the maximum delay fairness between coded and uncoded lower class services, and medium delay fairness for high class services.

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## 1. Introduction

Nowadays, passive optical networks (PON) have been a popular and reliable solution to access network, and there is fast growing trend of replacing the conventional copper networks with PON. Meanwhile, the demands for inter-optical network unit (ONU) communication in PON have been increasing with the rapid growth of peer-to-peer (P2P) communications, such as P2P file dissemination, online interactive game, audio/video conferencing, future cellular networks, data exchange in smart grid, and virtual private network (VPN) communication [1–5]. As a respond to these urgent demands, the next generation passive optical networks has been developed for years, and they can provide lots of

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opportunities for applying novel technologies to cope with the emerging challenges. One of these novel technologies is network coding (NC), which was firstly proposed by Ahlswede et al. [6]. Network coding refers to combining different incoming packet flows into one encoded packet flow without loss of information, rather than simple storing-and-forwarding or routing at network nodes. As innovative and promising technology, network coding is shown to improve throughput, simplify routing, and provide robustness against transmission errors and failures in various packet networks [2], and it has been introduced to PON only in recent years to support inter-ONU communication. Previous studies have proved that network coding technology in PON is capable to support secure VPN [5], reduce the packet loss and queuing delay in case of congestion [7], enable the OLT to save up to 50% on energy consumption by reducing the packet transmitting time [1,8], and increase downlink throughput by up to 50% in

inter-ONU communication without changing the PON hardware [3]. Thus, PON with network coding (NC-PON), which needs only software upgrade at a low cost and complexity, can not only achieve significant performance improvements but also be attractive to network operators.

Signaling process plays an important role in any kinds of communication networks, and also lays the foundation to fulfill network coding in PON. For the first time, Liu et al. in [1] proposed an NC signaling process to make the study on the implementation of NC-PON more complete. However, the signaling process scheme proposed in [1] requires that a source ONU is able to determine the destination ONU of each packet it sends upstream, which is similar to that in previous study [3]. Thus, a list of internet protocol (IP) or media access control (MAC) address to LLID mappings should be maintained by each ONU, so that the determination process of destination ONU can be implemented. Note that those mappings are created/updated whenever an ONU overhears a downstream frame that contains an IP datagram [3]. However, such a mapping list can be a threat to downstream security in PON, because an ONU may overhear packets belonging to other ONUs by faking a legal receiver with the help of the awareness of all LLIDs in PON. Thus, it is inappropriate for ONUs to maintain such a list, and a new signaling process is needed to guarantee both feasibility and security in NC-PON.

Moreover, as a key technology in NC-PON, dynamic bandwidth allocation (DBA) is worth studying. As yet, only a few efforts have been devoted to this issue. Miller et al. [3] and Fouli et al. [2] implemented their simulations in ethernet passive optical networks (EPON) integrated with network coding, using the classic interleaved polling with adaptive cycle time (IPACT) DBA algorithm proposed in [9]. IPACT can provide statistical multiplexing and efficient channel utilization. Thus, it works efficiently in traditional EPON. However, the IPACT in NC-PON cannot contribute to the reduction of additional queuing delay at the optical line terminal (the OLT) caused by network coding, not to mention the latency fairness between coded and uncoded inter-ONU flows. Kubo et al. [4] firstly focused on these problems in NC-PON, and proposed an adaptive priority scheduling (APS) algorithm to reduce the additional queuing delay at the OLT and improve the latency fairness among coded and uncoded inter-ONU flows. The main difference between APS and IPACT in NC-PON lies in the scheduling scheme. In APS, all the GATE messages are transmitted to ONUs in the next polling cycle only after all the REPORT messages are received by the OLT in previous polling cycle. Then, packets of each ONU can be allowed to transmit in the next polling cycle after the GATE message is received. Therefore, bidirectional inter-ONU flows in APS would experience a large end-to-end delay, for these flows had to wait at least two DBA cycles from the moment they arrived at the corresponding ONUs to the moment they were being transmitted to the OLT. This delay may be acceptable to the data exchanged among ONUs for smart grid applications, but may be unacceptable to some delay sensitive services of other common applications, such as voice and streaming multimedia data. Moreover, different delay, jitter and bandwidth requirements of differentiated classes of services had not been considered in APS, whereas queuing delay at the OLT and different polling orders in different DBA cycles would have negative impacts on those jitter sensitive services in APS. Hence, it is necessary to propose an efficient dynamic bandwidth allocation algorithm which can offer solutions to the above drawbacks of the existing DBA algorithms in NC-PON.

Toward those ends mentioned above, we propose a joint signaling and dynamic bandwidth allocation scheme in NC-PON. Note that both the signaling process and DBA scheme are based on multi-point control protocol (MPCP) arbitration mechanism, thus they are proposed jointly. Specifically, the signaling process is a founda-

tional part of our proposed joint scheme. In the signaling process, destination address information of packet flows in ONU queues is included in REPORT messages by using the pad fields, and these destination address information provides the basis to the inter ONU communication detection at the OLT. In addition, the proposed signaling process can not only avoid the potential threat to downstream security in previous schemes [1,3], but also be suitable for the proposed hybrid dynamic bandwidth allocation (HDBA) scheme. In HDBA, a DBA cycle is divided into two sub-cycles for applying different coding, scheduling and bandwidth allocation strategies to differentiated classes of services, thus quality of services (QoS) requirements in NC-PON can be supported. Furthermore, as network traffic load varies, the entire upstream transmission window for all REPORT messages slides accordingly, leaving the transmission time of one or two sub-cycles to overlap with the bandwidth allocation calculation time at the optical line terminal (the OLT), so that the upstream idle time can be efficiently eliminated.

The remainder of the paper is organized as follows: The rationale and the proposed signaling process for NC-PON are described in the following section. Section 3 presents the HDBA algorithm in NC-PON, including the proposed scheduling and bandwidth allocation schemes. Numerical analyses and simulations for performance evaluation are shown and discussed in Section 4. Finally, we conclude the paper in Section 5.

## 2. The rationale and the proposed signaling process for NC-PON

In this section, we first introduce the rationale for NC-PON, and then we propose a signaling process to help fulfilling network coding in PON.

### 2.1. The rationale for NC-PON

The rationale for NC-PON is illustrated in Fig. 1, which was firstly proposed in [7]. There are two packets ( $p_1$  and  $p_2$ ) to be exchanged between ONU 1 and ONU 2. As a result of the directional properties of the splitter/combiner, direct traffic between ONUs is not feasible. Any packet exchanged between ONUs is first transmitted to the OLT and then forwarded to the destination. Therefore, for PON without network coding as illustrated in Fig. 2(a), the two packets are first transmitted to the OLT and then broadcast by the OLT sequentially, which means two downstream transmissions are needed. However, if PON is integrated with network coding as illustrated in Fig. 2(b), the OLT will store the first transmitted packet  $p_1$  in its local buffer while not broadcast it downstream immediately. After the latter transmitted packet  $p_2$  is received, the OLT encodes  $p_1$  and  $p_2$  usually using a simple coding operation, such as bitwise exclusive-OR (XOR) operation (denoted by  $\oplus$ ), and then broadcast the single coded packet to the destination ONU 1 and ONU 2 by setting the logic link identifier (LLID) for multicast. After receiving the coded packet, ONU 1 (ONU 2) decodes this packet in the same XOR operation by using the ever transmitted packet  $p_1$  ( $p_2$ ) copy in its local buffer, and finally get the corresponding packet  $p_2$  ( $p_1$ ) with the packet  $p_1$  ( $p_2$ ) copy cleared up from its local buffer afterwards. Note that before  $p_1$  is transmitted upstream, the OLT should have had the knowledge of bidirectional communication between ONU 1 and 2, and these ONUs should have been informed which packets to be stored in local buffer when transmitting.

Network coding can also be applied to cyclic inter-ONU flows scenarios with no direct communication or bidirectional flows between any ONU pair [3]. For simplicity, we assume network coding is carried out only when an ONU group including bidirectional

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