A NOVEL DECENTRALIZED ETHERNET-BASED PASSIVE OPTICAL NETWORK ARCHITECTURE

A. Hadjiantonis, S. Sherif, A. Khalil, T. Rahman, G. Ellinas, M. F. Arend, and M. A. Ali,

Department of Electrical Engineering,
The City College and The Graduate School and University Center
of the City University of New York, NY, USA,
{antonis, sherif, akhalil, tanvir, gellinas, marend, ali}@ee.ccny.cuny.edu

A. Shami,

Department of Electrical Engineering,
Lakehead University, Thunder Bay, ON, Canada,
Abdallah.shami@lakeheadu.ca

***Abstract*:** This work proposes a novel fully distributed Ethernet over Star Coupler-based PON architecture. The architecture uses a collision-free DBA scheme in which the OLT is excluded from the implementation of the time slot assignment. To implement a distributed control plane, direct connectivity (communicability) between the ONUs should be in place without imposing any constraint on the PON topology. In addition to the added flexibility and reliability associated with a distributed architecture, the performance of the proposed decentralized Ethernet-based PON scheme and the associated bandwidth allocation algorithms are shown to be as efficient as their centralized counterparts.

I. INTRODUCTION

Ethernet-based Passive Optical Network (PON) technology is emerging as a viable choice for the next-generation broadband access network [1-8]. A PON is a point-to-multipoint fiber optical network with no active elements in the signal's path. It consists of a single, shared optical fiber connecting a service provider's central office (head end) to a passive star coupler (SC), which is located near residential customers. The SC is intentionally positioned a substantial distance away from the central office, but close enough to the customers in order to save fiber. Customers receive a dedicated short optical fiber (that connects them to the SC), but share the long distribution trunk fiber. All transmissions in a PON are performed between an Optical Line Terminal (OLT) and Optical Network Units (ONU's). Traffic from an OLT to an ONU is called 'downstream' (point-to-multipoint), and traffic from an ONU to the OLT is called 'upstream' (multipoint-to-point). Two wavelengths are used: typically 1310 nm (λ_{up}) for the upstream transmission and 1550 nm (λ_d) for the downstream transmission.

In the downstream direction, an EPON operates as a broadcast and select network. The OLT has the entire bandwidth of the channel to broadcast standard formatted 802.3 Ethernet frames to all ONUs. Each ONU extracts those packets that contain the ONUs unique Media Access Control (MAC) address. In the upstream direction, multiple ONUs share the transmission channel. Thus, the ONUs need to employ some arbitration mechanism to avoid collisions. In general, the OLT arbitrates the upstream transmissions by allocating an appropriate timeslot/Transmission Window (TW) to each ONU. An ONU is only allowed to transmit during the TW allocated to it by the OLT. Within each cycle, in order to inform the OLT about its bandwidth requirements, ONUs use REPORT Messages that are also transmitted along with the data in the TW. Upon receiving a REPORT, the OLT passes the message to a Dynamic Bandwidth Allocation (DBA) module responsible for bandwidth allocation decision. The OLT assigns the TWs via GATE messages.

Several bandwidth allocation schemes have recently been reported in the literature ranging for a static allocation to a dynamically adapting scheme based on instantaneous queue size in every ONU [5-8]. The simplest is the static TDMA scheme in which every ONU gets a fixed timeslot [5]. While this scheme is very simple, it results in inefficient upstream channel utilization since statistical multiplexing between the ONUs is not possible. A DBA scheme called Interleaved Polling with Adaptive Cycle Time (IPACT) based on Grant and Request messages has been presented in [8]. This scheme uses an interleaved polling approach where the next ONU is polled before the transmission from the previous one has arrived. This scheme provides statistical multiplexing for ONUs and results in efficient upstream channel utilization.

To date, the mainstream of these EPON bandwidth allocation schemes as well as the new IEEE 802.3ah EFM Task Force specifications [2] have been centralized–relying on a component in the central office (OLT) to provision upstream traffic. Hence, the OLT is the only device that can arbitrate time-division access to the shared channel. Since the OLT has global knowledge about the state of the entire network, this is a centralized control plane in which the OLT has a centralized intelligence. One of the major problems associated with a centralized architecture is the “single-point of failure problem”; that is the failure of the OLT will bring down the whole access network. It is the purpose of this work to propose a distributed solution to this problem, and in the process to prove that, in addition to the added flexibility and reliability, the performance of the proposed decentralized EPON architecture and the associated bandwidth allocation algorithms are at least as efficient as their centralized counterparts.

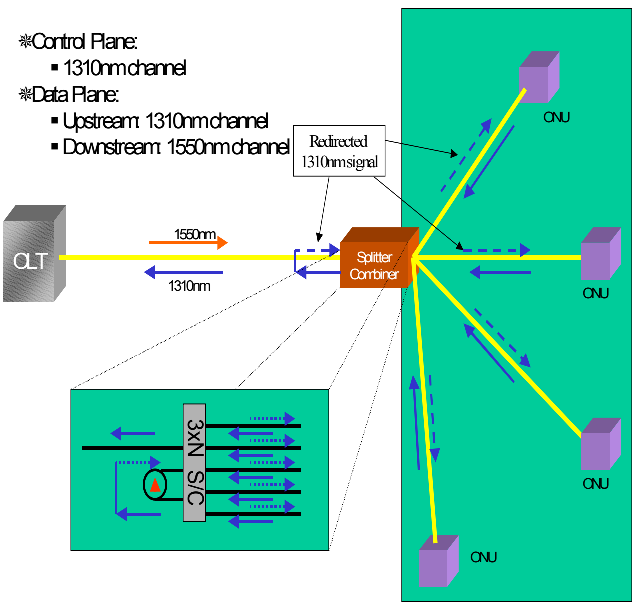

Figure 1: Proposed Distributed EPON Architecture.

Specifically, this work proposes a novel Ethernet over Star Coupler-based PON architecture. The architecture uses a fully distributed collision-free DBA scheme in which the OLT is excluded from the implementation of the time slot assignment. To implement a distributed control plane, direct connectivity (communicability) between the ONUs should be in place without imposing any constraint on the PON topology. In the proposed architecture, the ONUs exchange signaling and control information concerning their queue status and their transmission needs amongst themselves. Then, the ONUs simultaneously and independently run instances of the same DBA algorithm outputting identical bandwidth allocation results. Once the algorithm is run, the ONUs sequentially and orderly transmit their data without any collisions, eliminating the OLT's centralized task of processing requests and generating grants for bandwidth assignment.

II. THE PROPOSED DISTRIBUTED ALGORITHM

Fig. 1 shows the general architecture of this approach. As can be seen from Fig. 1, a portion of the optical signal power transmitted by an upstream transmitter (λ_{up}) toward the OLT will be redirected back and broadcasted to all ONUs. This can be achieved by connecting two ports of a 3 x N SC with each other through an optical isolator as shown in Fig. 1 [9]. Note that in addition to the conventional transceiver maintained at each ONU (a λ_{up} transmitter and a λ_d receiver), this approach requires an extra receiver tuned at λ_{up}. A baseband direct detection circuit is needed to detect the redirected control channel (λ_{up}) in order to recover the control update information.

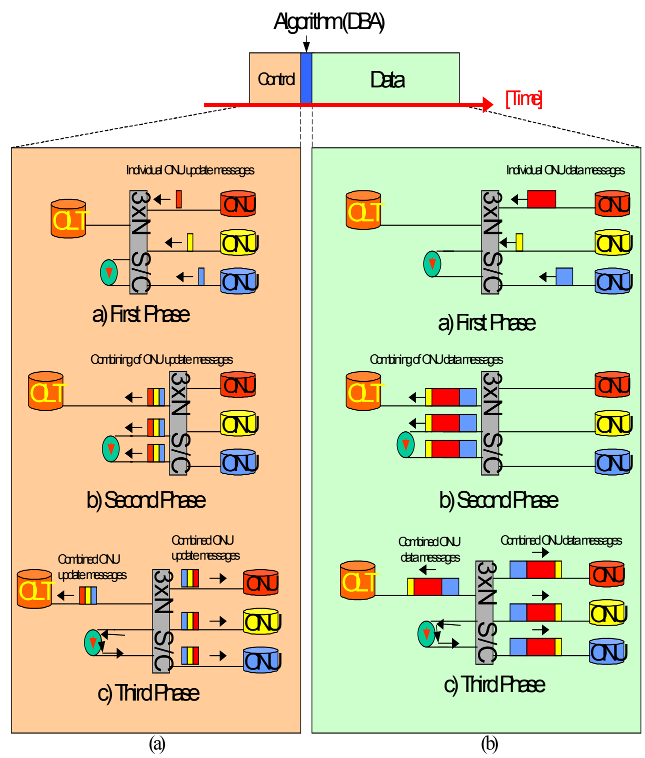

Figure 2: (a) Cycle updating process, (b) Transmission process.

This architecture assumes a cycle-based upstream link; a cycle is defined as the time that elapses between two executions of the scheduling algorithm. The cycle size can either have fixed, or variable length (confined within a certain upper bound) to accommodate the dynamic upstream traffic conditions. The cycle is divided into three periods; a static *update period* (control plane), a fixed *waiting period* (processing control messages and running the algorithm) and a dynamic *transmission period* (data plane).

The proposed cycle, along with the details of how the control plane performs the updating process is shown in Fig. 2a in three phases. Each ONU transmits its update control message in its own assigned fixed time update slot (first phase). These messages are then combined at the SC and a multiplexed update message is created (second phase). In the third phase, a fraction of the multiplexed control signal is transmitted through the first output port of the SC and propagates to the OLT (which could discard it, make use of it as a synchronization message, and/or process the control information). Another fraction of the multiplexed control signal is redirected back and broadcasted to all ONUs (through the isolator). A baseband direct detection circuit located at each ONU is then used to detect the redirected control channel (λ_{update}). The detected signal is then processed in order to recover the control data information belonging to each of the other *(N-1)* ONUs. Since there are only two operating communication wavelengths (λ_{up} and λ_d), signaling and upstream transmission take place on the same communication channel (λ_{up}) and the periods will appear sequentially as on the top of Fig. 2.

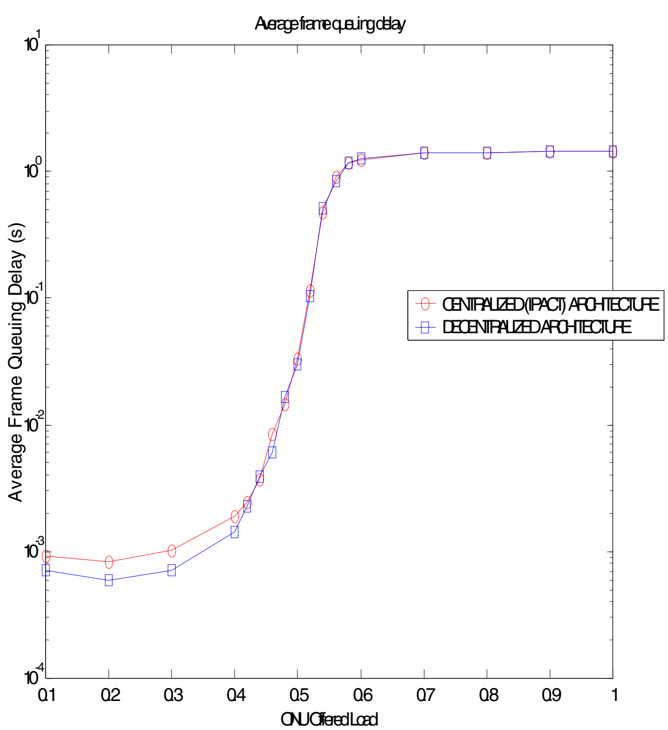

Figure 3. Average Frame Queuing Delay for Centralized and Decentralized architectures.

A. The First Period (Control Plane):

The **update period** is divided into N equal fixed time slots where N is the number of the ONU stations in the network. The update period is used for the ONUs to communicate their status and to exchange signaling and control message information with one another. Each ONU uses its own fixed time slot within the update period to transmit its control message. For simplicity, and to avoid collisions, the assignment of these N timeslots follows a fixed TDMA assignment since control messages are fixed in size. Note that the control slots in the proposed distributed scheme are all transmitted sequentially in one period (update period). This in contrast to the centralized schemes reported above [3-8], where the control slot (REPORT Message) of each ONU is transmitted along with the data in the TW allocated to it by the OLT. All control update messages are transmitted as Ethernet frames. Because the signaling information is segregated from the upstream traffic, signaling information can be timelier and complete thus increasing the efficiency of the Dynamic Bandwidth Allocation algorithm. These enhanced DBA algorithms would have the ability to support better QoS characteristics because transmission of the signaling information is not constrained by the shared data/control upstream channel associated with the centralized schemes.

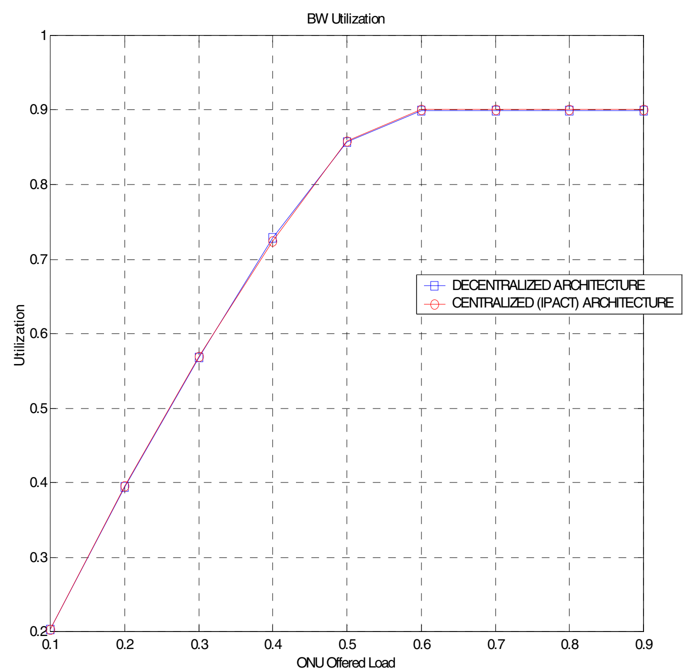

Figure 4. Bandwidth Utilization for Centralized and Decentralized architectures.

B. The Second Period (Algorithm Execution):

The second period of fixed length, is a **waiting period** (no upstream transmissions are allowed during this period) and is used for allowing the ONU's to process the information gathered from the multiplexed control message. Each ONU maintains a table with information about the state of the queues at each other ONU. This information is updated each cycle whenever the ONU receives a new multiplexed control message from all other ONUs. The DBA algorithm module uses the table maintained at each ONU. Note that instances of the same DBA algorithm are executed simultaneously and independently at each ONU. An execution of the algorithm yields a ***unique*** set of ONU assignments (w_i) ***identically*** produced in each ONU (w_i is the amount of bytes that an ONU is allowed to transmit in its TW). In other words, the algorithm should not incorporate any assumptions or randomness to handle exceptions. This is because several instances of it will run locally and independently at each ONU.

C. The Third Period (Data Plane):

The third period or (**transmission period**) is essentially a giant slot used for actual upstream data transmission. During the transmission period, the ONU's follow exactly the allocation scheme the algorithm produced (i.e. their transmissions start at specific times and last for specific bytes) as shown in Fig. 2b. Note that the order of ONU's transmission may be different in each cycle and need not be fixed; but rather is a function of the ONU's traffic demand. This is a major advantage compared to the fixed transmission order proposed in [8].

II. PERFORMANCE EVALUATION

The traffic model used here is the same as that reported in [8] where each ONU is modeled to be fed by a number of ON/OFF sources, each with a Pareto distribution governing the lengths of the ON/OFF periods, to capture the self-similar nature of Ethernet traffic. To compare the performance results of the proposed decentralized model with that of the centralized scheme (IPACT) of [8], we use the same system parameters used therein; a system with 16 ONUs, access link data rate from users to an ONU of 100 Mb/s, and a 1 Gb/s upstream link data rate (from an ONU to the OLT). Several bandwidth allocation algorithms were studied in [7-8], namely: fixed, limited, gated, constant credit, and linear credit. Amongst these algorithms, the limited (where the OLT grants the requested number of bytes, but no more than a given predetermined maximum), was shown to exhibits the best performance. Due to the space limitations, we use the simple limited DBA algorithm used in [8] for comparing our distributed architecture versus that of the centralized scheme reported therein.

Fig. 3 presents the mean frame queuing delay, for both the centralized and distributed architectures using the *Limited* DBA algorithm, as a function of an ONU's offered load. In the case of the proposed decentralized approach, the order of the transmitting ONUs in a given cycle is not fixed (as in IPACT), but rather ordered based on the allocated TW determined by the DBA algorithm (the highest allocation transmits first; ties are broken by the ONU ID). From the results, it is observed that the decentralized approach improves IPACT in terms of the average frame delay at low loads. This is because by interchanging the order of transmissions, a given ONU's update message is closer in time to its corresponding transmission. Thus, a more current depiction of its buffer status is governing the transmission. As the load increases more ONU's request more than the maximum allowed window, and thus more get the same allocation (maximum window). This, in turn, makes the advantage of the interchanged order of transmission to vanish.

Fig. 4 shows the channel bandwidth utilization for both the centralized and distributed architectures using the *Limited* DBA algorithm, as a function of an ONU's offered load. As can be seen from the figure, the performances of the two architectures are almost identical, with the centralized approach exhibiting a slight advantage (less than 1%).

Finally, it is important to emphasize that, in general, distributed architecture-based DBA algorithms (future work) would outperform those of the centralized architecture-based DBA algorithms reported in [7-8]. This is because a distributed DBA algorithm takes into account all other ONU requests when allocating a TW to a given ONU. This in contrast to the centralized architecture reported in [8], where all the proposed DBA algorithms take into account only that particular individual ONU request when allocating a TW to it.

IV. CONCLUSIONS

This work has proposed a novel decentralized Ethernet over Star Coupler-based PON architecture. The performance of the proposed distributed EPON architecture and the associated bandwidth allocation algorithms are shown to be as efficient as their centralized counterpart. While the proposed distributed architecture increases the complexity of the ONU, however, the added flexibility and reliability of such architecture might justify the extra cost. Furthermore, because the signaling information is segregated from the upstream traffic, signaling information can be timelier and complete thus increasing the efficiency of the DBA algorithm. These enhanced DBA algorithms would have the ability to support better QoS characteristics because transmission of the signaling information is not constrained by the shared data/control upstream channel associated with the centralized schemes.

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