Decentralized Media Access vs. Credit-Based Centralized Bandwidth Allocation for LR-PONs

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***Abstract*—Several centralized dynamic bandwidth allocation algorithms have been proposed for Ethernet Passive Optical Networks (EPONs), making the optical line terminal (OLT), located in the central office, the intelligent device that arbitrates time-division access to the shared upstream channel. When the network span is extended to 100 km and beyond, as suggested by next generation long-reach PONs (LR-PONs), the increased propagation delays severely degrade the performance of these algorithms since they are based on bandwidth negotiation messages frequently exchanged between the optical network units (ONUs) and the OLT. In this paper, we propose a decentralized media access scheme for the emerging LR-PON that would enable sooner transmission of upstream packets. We accompany this scheme with centralized control over the network. Through simulation, we compare the performance of the proposed scheme with centralized credit-based schemes that are thought to be able to mitigate the degradation of centralized schemes in LR-PONs. Results show that the proposed scheme is less affected by the network extension and can reduce average packet delays beyond those of credit-based schemes.**

Keywords-Decentralized, dynamic bandwidth allocation (DBA), long-reach passive optical network (LR-PON).

I. Introduction

The exponential increase in users' demand for various broadband applications, accompanied by access networks not being scaled up proportionately, has created a "last mile" bottleneck in the telecommunications infrastructure [1]. To alleviate this bottleneck, new access technologies came to play, which bring the high capacity of optical fiber into access areas, offering the potential for up to 100Mbps and more to each end-user. *Passive optical networks* (PONs) have been widely chosen for deploying these optical access networks [2]. This is because a PON has no active network elements in the field, but only employs passive optical components. It also enables *central office* (CO) equipment to be shared by a large number of customers without deploying much fiber as with a point-to-point architecture. Thus, by eliminating the power supply along the fiber path, which saves a large portion of *operational expenditures* (OpEx), and by sharing significant portions of the network's *capital expenditures* (CapEx) among multiple users, PON has demonstrated itself as the most promising and cost-effective broadband access network [3]. The combination of low-cost Ethernet equipment with low-cost passive optical components has also received great attention from both industry and academia in recent years.

Now that advances in optical communications technologies have allowed for longer transmission and distribution distances for PONs, research focus has shifted to the scalability of PONs with longer reaches and higher split ratios, thereby increasing the number of served subscribers and further reducing the cost. Extending the reach of the network allows network operators to consolidate multiple COs in more conveniently located facilities, while higher splitting ratios allow the *optical line terminal* (OLT) and the feeder fiber to be shared among a larger number of users. The concept of *long-reach PONs* (LR-PONs) was therefore proposed as a more cost-effective solution for optical access networks [5]. By exploiting optical amplifiers and *wavelength-division multiplexing* (WDM) technologies, a LR-PON may extend the coverage of a traditional PON to hundreds of kilometers, while increasing its splitting ratio from 64 to more than 1024. By extending the geographic coverage, a LR-PON can in some locations remove the requirement for a metro tier in the telecommunications network hierarchy [6], and combine access and metro networks into a single integrated system, as illustrated in Fig. 1.

LR-PONs come with many research challenges, one of which is the bandwidth allocation problem under the increased propagation delays between the OLT and ONUs [6]. There have been many suggested architectures and demonstrations for LR-PONs in the literature. Despite the various architectures, the logical connection between the OLT and ONUs remains the same. Just as traditional PONs, all downstream transmissions (from the OLT to ONUs) are done in broadcast-basis through a passive splitter. In the upstream direction however, the network is a multipoint-to-point network; multiple ONUs all transmit toward one OLT through a common passive combiner. Some *media access control* (MAC) mechanism is therefore needed to fairly coordinate ONU transmissions and avoid data collisions.

Although the future seems to head for WDM in access networks, allowing each ONU to operate on its own wavelength, *time division multiple access* (TDMA) has been adopted in both PON standards; Ethernet PON (EPON) and Gigabit PON (GPON). Centralized *dynamic bandwidth allocation* (DBA) has been widely used for TDMA PONs [7, 8], in which the OLT arbitrates time division access on the shared upstream channel by assigning different timeslots for each ONU, thereby sharing the optical capacity among subscribers. The performance in centralized allocation schemes depends on the ONU *round-trip time* (RTT) since it imposes a

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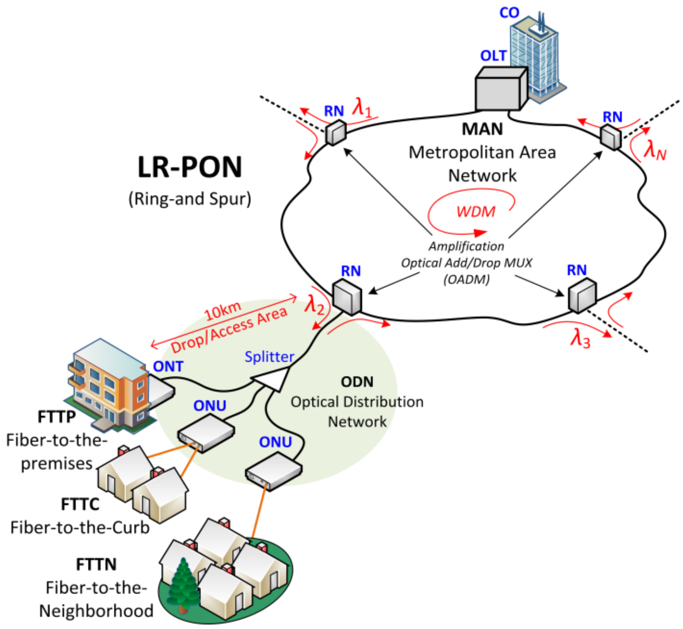


Fig. 1. A LR-PON combining metro and access networks.

delay on the CO-ONU control loop. The reach extension of LR-PONs thereby introduces challenges to the medium access control layer as the RTT may grow from today's 200µs (20 km reach) to 1ms (100 km reach). With this increased RTT, the performance of centralized allocation schemes is degraded.

In [9], we initially proposed a decentralized media access scheme, in which the ONUs take turns transmitting in a round-robin fashion without waiting for permissions from the OLT. This gives upstream packets the chance to be transmitted much sooner and decreases their average delay. Centralized operator control is also maintained over the network to set and ensure *service level agreements* (SLAs). In this paper, we review our proposed scheme, suggest a less expensive implementation, and compare its performance against centralized credit-based schemes which also allow sooner transmission of packets and could mitigate the degradation of LR-PONs.

The rest of this paper is organized as follows. Section II is a review of centralized bandwidth allocation, explaining how its performance is highly affected by extending the network span. In Section III, we introduce the principles of our decentralized media access scheme. Section IV presents illustrative numerical results and Section V concludes the study.

II. CENTRALIZED DYNAMIC BANDWIDTH ALLOCATION

In order for the OLT to make accurate timeslot assignments in centralized arbitration schemes, it needs to know the exact buffer state of a given ONU. Each ONU thus needs to report its bandwidth demand to the OLT before the OLT allocates it a timeslot. For this purpose, the IEEE 802.3ah Ethernet standard defines a *multipoint control protocol* (MPCP), which is a signalling protocol that supports bandwidth negotiation between the OLT and ONUs. The protocol uses two 64-byte MAC-control messages for bandwidth negotiation; a REPORT for the ONU to report its queue status to the OLT, and a GATE to deliver the OLT's bandwidth allocation decision to the ONU, granting it media access and polling it for its next REPORT. It should be pointed out that MPCP is not concerned with any particular bandwidth allocation scheme or scheduling algorithm, allowing them to be vendor-specific [1].

The propagation delays between the OLT and ONUs result in a control-plane delay for centralized allocation schemes. The OLT does not have real-time network-state information. Instead, it has a delayed version caused by the propagation delay. Moreover, after reporting its buffer status, each ONU must wait at least a RTT before being granted media access. In this section, we review the delays associated with a centralized polling algorithm and further explain how its performance is highly affected by extending the network span.

A. *Interleaved Polling with Adaptive Cycle Time (IPACT)*

Interleaved polling is a pipelined timeslot assignment that allows the OLT to send a grant message to the next ONU before data and the piggy-backed report message arrive from the previously polled ONU [10]. This is feasible since upstream and downstream channels are separated, and since the OLT maintains relevant information about each ONU in its polling table. In IPACT, the OLT polls ONUs and grants them timeslots in a round-robin fashion corresponding to their reported queue status. The OLT employs SLAs of end users by setting an upper-bound for the allocated bandwidth (window size) of each ONU. To do so, several schemes were investigated in [10], of which the *limited service* (LS) was found to exhibit the best performance. In LS, the OLT grants an ONU a transmission window for the number of bytes requested, but no more than a certain maximum;

$$W_i = \min(R_i, W_{i,\max}) \quad (1)$$

where R_i is the requested window for ONU$_i$, W_i is its granted window, and $W_{i,\max}$ is its maximum allowed window. Such a scheme is the most conservative as it assumes that no packets arrive after an ONU sends its report, and has the shortest cycle.

B. *Polling Delays*

Figure 2 is a space-time diagram illustrating the different types of delays a packet may experience in a centralized polling scheme; *reporting*, *grant*, and *queuing* delays [1]. Only two ONUs are shown for simplicity, and they are shown to be at different distances from the OLT. It is worth mentioning that these three types of delays are *pre-transmission* delays; delays that occur prior to transmission. Once packet transmission starts, two more delays are introduced; a *transmission* delay and a *propagation* delay. While pre-transmission delays depend on the DBA algorithm, the other two delays depend on the network and packet lengths regardless of the algorithm. However, it can be seen that grant delays contain both transmission and propagation delays, which makes pre-transmission delays of centralized polling also sensitive to and affected by extending the reach of the network. The increased propagation delays of LR-PONs therefore lead to increasing the DBA response time and result in increased packet delays.

C. *Credit-Based Schemes*

Credit-based schemes were proposed to account for packets that arrive at an ONU right after it sends its report. Otherwise,

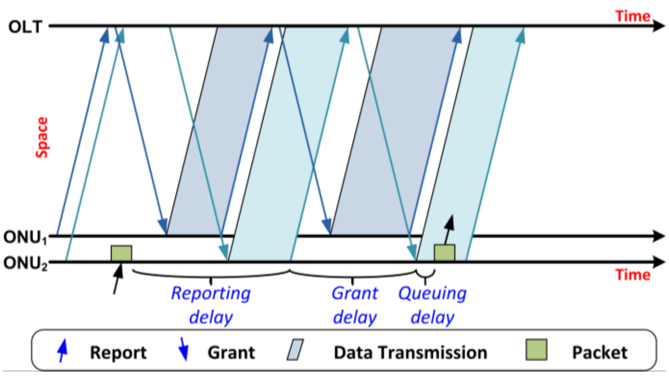


Fig. 2. Delays of centralized polling.

these packets will normally have to wait until they are first reported and then granted transmission. Because of the long RTT between each ONU and the OLT in future LR-PONs, it is thought that credit-based schemes could mitigate the degraded performance of centralized polling. In this work, we consider two credit-based schemes that were proposed for IPACT in [1, 10]. The first is the *constant-credit* (CC) scheme, in which a fixed credit is always added to the requested window size and considered in the granted window size;

$$W_i = \min(R_i + \alpha W_{i,\max}, W_{i,\max}), \quad 0 < \alpha < 1 \qquad (2)$$

where α is a constant and $\alpha W_{i,\max}$ is the constant added credit, which in this expression is a proportion of the ONU's maximum allowable window. This scheme usually gives an ONU a transmission widow slightly larger than requested, so that it can accommodate some or most of the packets that had arrived after sending its report. The choice of the credit size is essential and has a direct impact on the network performance. A credit that is too small will not be able to improve packet delays a lot, whereas a credit that is too large may degrade the bandwidth utilization of the upstream channel.

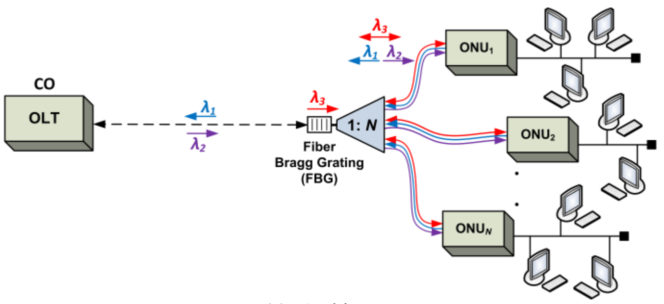
The second credit scheme is the *linear-credit* (LC), in which the credit is proportional to the requested window size;

$$W_i = \min(\alpha R_i, W_{i,\max}), \quad \alpha > 1 \qquad (3)$$

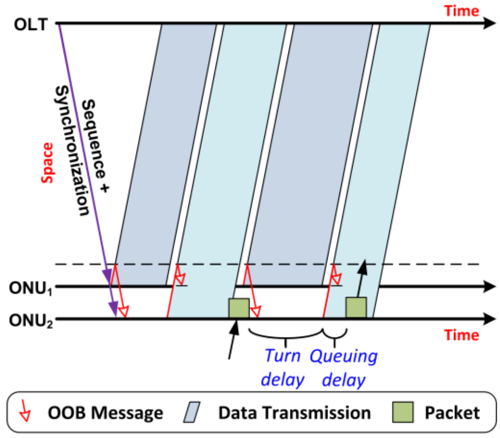
The reasoning behind this scheme is that network traffic possesses a certain degree of predictability. A long burst of data is likely to continue for some time into the future. Correspondingly, the arrival of more data during the last cycle may signal that a burst of packets is taking place [10].

III. Proposed Decentralized Media Access Scheme

Decentralized media access schemes have been proposed before for traditional PONs. Some schemes were contention-based that do not ensure bandwidth guarantees [11], while others for instance aimed to support distributed DBA [12]. Most of these schemes required a fully broadcasting-PON that causes significant upstream power loss. Decentralized schemes may however show significant improvement over centralized schemes when ONUs are located very far from the CO. In [9], we proposed a decentralized media access scheme, in which ONUs basically take turns transmitting in a round-robin fashion according to some pre-defined sequence. To ensure that an ONU does not monopolize the upstream channel, each ONU is allowed to locally decide how much it will send (according to its buffer status) but without exceeding a certain maximum. Such a scheme operates on a cyclic basis with adaptive cycle duration proportionate to the size of upstream transmissions, which is why we call it *Taking Turns with Adaptive Cycle Time (TTACT)*. This scheme introduces two main challenges; communication between ONUs with no upstream power losses nor additional fiber deployment, and maintaining centralized operator control over the network.



(a) Architecture



(b) Space-time diagram

Fig. 3. OOB loop-back technique using a wavelength reflector.

A. *Acquiring Communication between ONUs*

To efficiently utilize the upstream channel, an ONU must time its transmission such that it arrives at the OLT right after the previous ONU's transmission. This can be done by either monitoring the preceding ONU's data transmission to detect when the upstream channel becomes idle (i.e. carrier sensing), or by receiving a message declaring how many bytes the preceding ONU will send and thereby knowing when to start its transmission. The former can be accomplished using the optical loop-back technique used in [12], in which the 1: N star coupler is replaced with a 3: N coupler with two ports connected together through an optical isolator. However, this technique has a major drawback; the upstream power loss due to reflection, which may place boundaries on the maximum OLT-ONU distance or the splitting ratio. We therefore propose using *out-of-band* (OOB) communication between ONUs on a control wavelength to manage media access. This wavelength is reflected back, creating a multipoint-to-multipoint network among ONUs, by attaching a *fiber Bragg grating* (FBG) to the splitter/combiner (SC), as shown in Fig. 3(a). The FBG is a low cost passive filter (20-100$), which is a periodic variation in the refractive index of the fiber core. This variation makes it act as a mirror that returns one specific wavelength (or waveband) and passes all the others. It is therefore sometimes

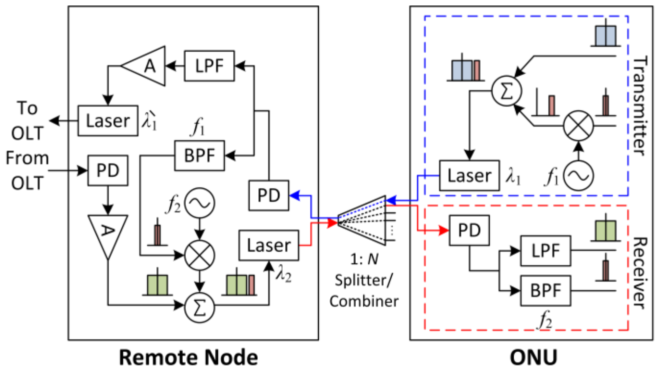


Fig. 4. OOB loop-back technique using subcarrier multiplexing.

called a reflective band filter [13]. At the beginning of its transmission, each ONU will send a very short time-stamped control frame announcing how many bytes it intends to send, as illustrated in Fig. 3(b). This with regarding the fact that ONUs have a common time reference achieved by the OLT's downstream broadcasting transmissions. Upon receiving the frame, the following ONU will schedule its transmission to arrive at the OLT right after the previous transmission leaving a small guard interval. That way, the delays of the proposed decentralized scheme; *turn* and *queuing* delays, can be independent of the network reach.

Even though this technique would require additional ONU transceivers, they are only required to operate at rates less than 100Mbps, which would significantly reduce their cost. There are also other implementations that may not require additional transceivers. For instance, subcarrier multiplexing could be used to transmit both upstream data and control signals using the same laser. For ONUs to receive this subcarrier either additional receivers are installed or wide receivers are accompanied with two electrical filters, as shown in Fig. 4.

B. *Centralized Operator Control*

Centralized operator control is necessary to manage bandwidth allocation according to user SLAs. To maintain such control over the proposed scheme, ONUs will occasionally receive control parameters from the OLT that control how the ONUs transmit. These parameters include the ONUs' transmission sequence and the maximum allowable transmission window for each ONU ($W_{i,\max}$). The key feature of our scheme here is that ONUs do not have to wait for these parameters each time they transmit. These control parameters merely supervise and optimize the upstream transmission process. Some of these parameters are only changed according to SLAs or operator managements, whereas others may change with response to network conditions. The ONUs could be designed to operate on default parameter values or last received ones. That way, the OLT needs only to send control frames when a parameter is required to change. On the other hand, parameters that are changed within each cycle, such as an ONU's transmission window (W_i) and its timing, are now locally managed between ONUs.

MPCP can allow such control, since it does not specify a certain DBA. It defines control messages between a master unit (OLT) and slave units (ONUs) connected to a point-to-multipoint segment. Besides the information of source, destination, timestamp, etc., a generic MPCP frame reserves 42-byte "opcode-specific fields" for additional functions [1]. It could therefore be used in our decentralized scheme to deliver the control parameters.

IV. Numerical Results

In this section, we compare our proposed decentralized scheme TTACT with centralized polling using the LS discipline and both credit-based schemes. We consider a 100 km LR-PON with a 10 km drop section. As in previous studies [10], the network consists of an OLT and 16 ONUs. The ONUs share an uplink channel of 1Gbps, whereas from the access side, packets arrive at each ONU from connected end-users at 100Mbps. Each ONU has a finite memory buffer of 10 Mbytes. We use Ethernet network traffic (64 to 1518-byte frames), while also accounting for frame preambles and inter-frame gaps. To reflect the self-similarity property of Internet traffic, user traffic is generated using the model described in [1, 10], with a Hurst parameter of 0.8. The cycle duration is set to 5ms, which is found to be very convenient at the 100km span. Inter-transmission guard intervals are set to 5μs. For credit-based schemes, we choose α to be 0.15 and 1.5 for constant-credit and linear-credit, respectively. These values were found to achieve optimum performance. For our proposed scheme, the FBG attached to the SC is placed in the middle of the 10 km drop section (95 km from the OLT), while the transmission rate of the OOB control channel is 100Mbps.

A comparison of average pre-transmission delays for the discussed schemes is shown in Fig. 5, when ONUs are placed randomly within a 5 km distance from the combiner. The credit-based schemes are shown to perform worse than LS under loads higher than 0.8, but they are better under normal loads in a LR-PON. The decentralized scheme still shows significant improvement over centralized schemes even under heavy loads. This is basically because a packet no longer needs to be reported and then wait for a grant. Instead, the packet waits for its corresponding ONU's turn to transmit. Figures 6 and 7 show the effect of extending the network on average pre-transmission delays and total packet delays (including transmission and propagation delays), respectively. For this, all ONUs are at the maximum distance, while the coupler is always 5 km away from the ONUs since the extension in the network is usually in the feeder section (fiber from the OLT to the drop section). Extending the feeder shows to have completely no effect on pre-transmission delays of the decentralized scheme since they are independent of the feeder

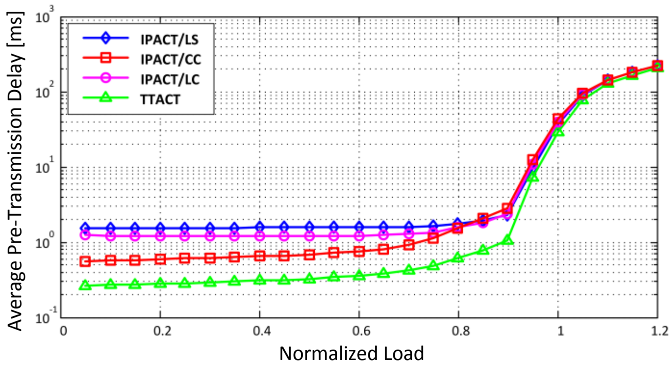


Fig. 5. Average pre-transmission delays comparison.

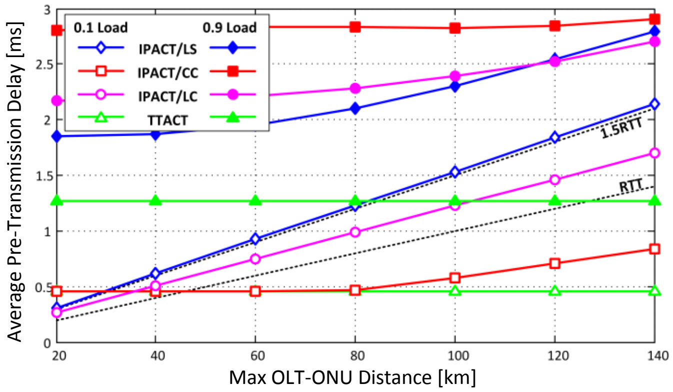


Fig. 6. Effect of extending the network on average pre-transmission delays.

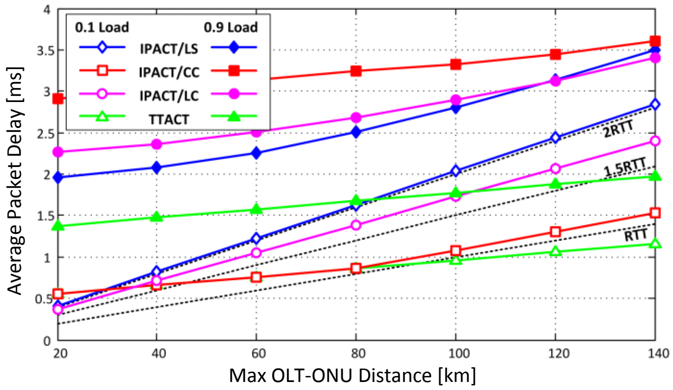


Fig. 7. Effect of extending the network on total packet delays.

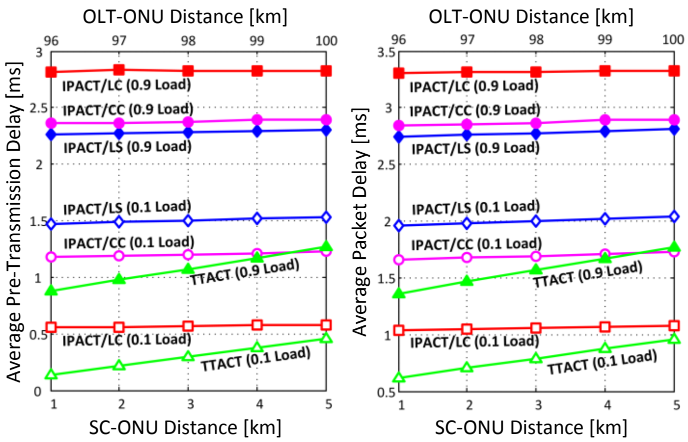


Fig. 8. FBG-ONU distance extension effect on delays.

length. IPACT with limited service is shown to be distance-dependent with a minimum of about 1.5RTT for pre-transmission delays and of 2RTT for total delays. Credit-based schemes were able to break these lower bounds only under light loads, but they still remain distance dependent. They are unable to make total delays go below the RTT, which is only possible using the decentralized media access scheme, as it gains more advantage with extending the network.

To show how the proposed decentralized scheme will perform under the worst possible scenario in a 100 km LR-PON, we maximize the distance between the FBG and the ONUs, since the scheme is affected by the ONUs distances from the reflector rather than their distances from the OLT. Figure 8 presents a general overview of both average pre-transmission delays and total delays as ONUs are moved further from the splitter (located 95 km away from OLT) with increments of 1km. Although the performance of decentralized TTACT is shown to degrade, it still maintains better performance than centralized schemes. The duality of credit-based schemes is also shown in the figure, as they succeed in reducing delays below those of the limited service under light loads, but cannot maintain the same performance under heavy loads. In fact, the credit scheme with the best performance under light loads is the worst under heavy loads.

V. Conclusions

In this paper, we addressed the problem of dynamic bandwidth allocation in a Long-Reach PON. We proposed a decentralized scheme to remedy the effect of the long CO-to-users control loop that degrades the performance of centralized polling schemes. We allow ONUs to take turns transmitting, while maintaining some form of centralized control to partially manage bandwidth distribution and service differentiation according to service agreements. That way, our proposed approach allows for low packet delays and centralized control simultaneously. Numerical results show that the average upstream packet delay can be significantly reduced below that of centralized schemes, even when using credit-based schemes. The improvement in the delay performance is mainly due to the delays being independent of the ONUs distances from the OLT, but dependent on their distances from the nearby reflector. This also leads to more performance gain over centralized approaches as the feeder length is extended.

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