Taking Turns With Adaptive Cycle Time a Decentralized Media Access Scheme for LR-PON

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***Abstract*—The extended network span of next-generation long-reach passive optical networks (LR-PONs) results in extremely long propagation delays that severely degrade the performance of centralized bandwidth allocation algorithms. This is because these algorithms are based on bandwidth negotiation messages frequently exchanged between the optical line terminal (OLT) in the central office and optical network units (ONUs) near the users, which become seriously delayed when the network is extended. To address this problem, we propose a decentralized media access scheme for emerging LR-PONs to make the performance independent of the physical length between the OLT and ONUs. We also maintain centralized control over the network, usually missed in conventional decentralized schemes, to support and manage quality of service according to user service level agreements. The scheme thus combines decentralized media access with centralized control to meet the special requirements of emerging LR-PONs. We investigate the performance of the proposed scheme in contrast with centralized schemes under worst case conditions. We also explore various approaches to further enhance the performance of our scheme. Simulation results show that the average upstream packet delay can be decreased by 60% while also maintaining a high throughput.**

***Index Terms*—Decentralized, dynamic bandwidth allocation (DBA), long-reach passive optical network.**

I. Introduction

THE explosive increase in bandwidth demand, caused by users pursuing emerging and expanding web applications and services, has led to new access network architectures that bring the high capacity of the optical fiber closer to residential homes and small businesses, from where technologies such as DSL or wireless can take over. Passive optical networks (PONs) have often been the technology of choice for deploying such optical access networks. This is because a PON has no active components in the field, but only employs passive optical components such as fibers and splitters and, therefore, reduces much of the network operational costs. The transmission fiber and central office (CO) equipment are shared by a large number of customers without deploying much fiber as with point-to-point architectures. Compared to other access technologies, PONs provide high bandwidths at relatively lower costs, allow longer distances between customers and the CO, and also allow easy upgrades to higher bit rates [1].

With the widespread deployment of PONs all over the globe [2], research focus has shifted to their scalability with longer reaches and higher split ratios, thereby increasing the number of served customers and further reducing the cost. Extending the reach of the network is thought to reduce the number of CO premises allowing network operators to consolidate multiple COs in more conveniently located facilities. Higher split ratios allow sharing the optical line terminal (OLT) optics and electronics among more users, more efficiently utilizing the head-end rack space for a higher density OLT and simplifying fiber management [3]. The concept of a long-reach PON (LR-PON) was thus proposed as a more cost-effective solution for optical access networks [3]–[7]. A LR-PON exploits optical amplifiers and wavelength-division multiplexing technologies to extend the coverage from the traditional 20 km to more than 100 km, while increasing the split ratio from 64 up to 1024 and beyond. In some locations, extending the geographic coverage may allow combining access and metro networks into a single integrated system.

There have been many suggested architectures and demonstrations for LR-PONs in the literature [5]–[7]. Most architectures can be characterized under "ring-and-spur" and "tree-and-branch," as shown in Fig. 1, depending on whether the CO is connected to the access zones by a feeder that is a strand of fibers (tree) split to multiple fibers (branches) at a local exchange (LX), or a feeder composed of a fiber ring and optical add-drop multiplexers placed in remote nodes (RNs) [7]. In both architectures, several PONs are multiplexed into the shared fiber and served together by a single CO, while optical network units (ONUs) are put close to the LX/RN (within a 10 km drop zone). Each PON segment basically uses different upstream and downstream wavelengths to communicate with the CO and enables better utilization of the feeder capacity.

LR-PONs come with many research challenges. In this paper, we focus on bandwidth allocation under the increased propagation delays. Despite the various architectures of LR-PONs, the logical connection between the OLT and ONUs, illustrated in Fig. 2, remains the same but with its distance extended. All downstream transmissions are done in broadcast basis, while in the upstream direction all ONUs transmit to the OLT through a passive star coupler (SC), also known as the splitter/combiner. Some media access mechanism is, therefore, required in the upstream direction to coordinate ONU transmissions and avoid data collisions, especially when ONUs are unable to listen to each other due to the directional property of the combiner.

Manuscript received April 28, 2011; revised June 25, 2011, July 31, 2011; accepted August 27, 2011. Date of publication September 12, 2011; date of current version November 09, 2011. This work was supported in part by the National Plan for Science and Technology of Saudi Arabia under Grant 09-ELE667-02.

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Digital Object Identifier 10.1109/JLT.2011.2167741

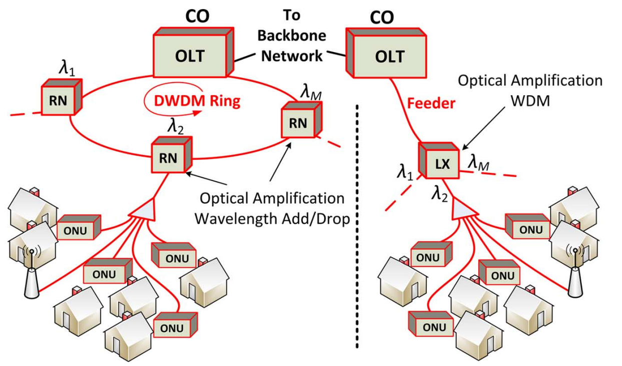

Fig. 1. Basic LR-PON architectures: ring-and-spur (left) and tree-and-branch (right).

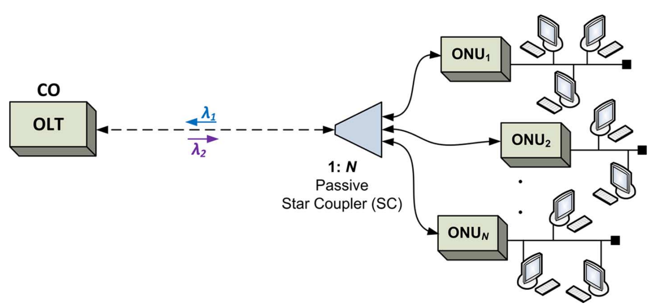

Fig. 2. Logical connection between OLT and ONUs in an LR-PON.

Time-division multiple access has been adopted in both PON standards; Ethernet PON (EPON) and Gigabit PON, and centralized bandwidth allocation schemes have been used, making the OLT arbitrate time-division access on the shared upstream channel [8], [9]. The performance in such schemes is affected by the ONU's round-trip time (RTT) since it imposes a 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 200 μs (20 km reach) to 1 ms (100 km reach). With this increase in RTT, the performance of centralized schemes is highly degraded. Thus, developing allocation schemes that deliver adequate service despite the increased RTT in LR-PON is highly desirable.

Recent researches address the problem of bandwidth allocation in LR-PON, under its increased propagation delays, by proposing new centralized bandwidth allocation schemes (see, e.g., [10]–[12]). However, because they are centralized, their performance is still affected by the extended network reach and their packet delays cannot go below certain bounds. In this paper, we propose a different approach. We develop decentralized media access solutions that are independent of the RTT and, therefore, have characteristics that make them better suited for LR-PONs. To the best of our knowledge, decentralized schemes have not yet been addressed under the context of LR-PONs. We believe they should be considered and their performance and cost should be evaluated for these next-generation networks. In our proposed scheme, 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 delays. We also maintain centralized operator control over the network to manage user service level agreements (SLAs). In our study, we focus on the EPON standard.

The rest of this paper is organized as follows. In Section II, we review the basis of centralized bandwidth allocation, explaining how its performance is highly affected by extending the network. Next, we introduce the principles of our decentralized scheme in Section III. In Section IV, we consider various enhancement strategies to the proposed scheme. Section V presents numerical results and Section VI concludes this study.

II. Centralized Dynamic Bandwidth Allocation

In centralized allocation schemes, the OLT arbitrates time-division access on the shared channel. To make accurate timeslot assignments, the OLT needs to know the exact buffer state of a given ONU. Conventionally, *polling* schemes have been used, which are based on *report* and *grant* messages. In such schemes, the OLT keeps a polling table with an entry for each ONU to record both its RTT and buffer status. A report message is sent by an ONU to inform the OLT of the amount of buffered data it needs to send. A grant message is used by the OLT to poll an ONU and grant it a transmission window, which may correspond to the ONU's bandwidth demand. Therefore, in polling schemes, the ONUs do not need to monitor the network nor negotiate new parameters. However, polling schemes suffer from a control-plane delay caused by the propagation delays between the OLT and ONUs, as further discussed later.

Dynamic bandwidth allocation (DBA) generally involves two coexisting processes; determining the sizes of the timeslots (grant sizing) and scheduling their times/order (grant scheduling). The two processes can be carried out using one of two frameworks: *offline* scheduling or *online* scheduling [9]. The former is also known as collective scheduling [13], in which the DBA agent has to first collect all the report messages before grant sizing and scheduling. This enables a globally optimized decision, by which any excess bandwidth from lightly loaded ONUs can be fairly and accurately distributed among heavily loaded ONUs while also being granted in an optimized order. However, using a primitive offline centralized scheduling scheme will result in an idle time of one RTT, which is the time from collecting all reports till the first ONU transmission reaches the OLT. This idle period can be eliminated by using parallel offline threads, i.e., multithread polling [10], which was proven to be better than using a single offline thread.

In online scheduling, the DBA decision is made *straightaway* based solely on the received report. In this type of scheduling, ONUs are typically granted media access in a round-robin fashion. *Interleaved polling with adaptive cycle time* (IPACT) is an example of online scheduling and has been a pioneer centralized algorithm for EPON [14]. As illustrated in Fig. 3, it employs a pipelined timeslot-assignment allowing the OLT to send a grant message to the next ONU before data and report messages arrive from previously polled ONUs. This is feasible since upstream and downstream channels are separated, and since the OLT maintains relevant information about each ONU in the polling table. The OLT employs SLAs of end users by setting an upper bound to the allocated bandwidth (grant size) of each ONU. To do so, several grant sizing schemes were investigated in [14], of which the limited service (LS) was found to exhibit the best performance. Using LS, the OLT grants an ONU the number of bytes requested, but no more than a certain maximum

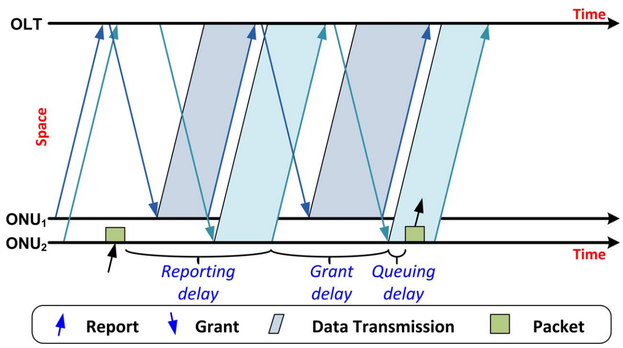

Fig. 3. Centralized polling with online scheduling.

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

where R_i is the requested transmission window (report) for ONU_i, $W_{i,\max}$ is its maximum allowed window, and W_i is its granted window. Such a scheme assumes no packets arrive after the report is sent and thus has the shortest cycle.

To date, research continues on adding to and further improving IPACT [15]–[17]. It has also been studied for LR-PON in [12], where it was modified to support different SLAs by differentiating the ONUs' maximum transmission windows. In this paper, we compare the performance of our decentralized scheme with that of IPACT. In the next sections, we analyze the different types of delays of centralized DBA schemes, and show how its performance is degraded when the distance is extended as within LR-PON.

A. Centralized Polling Cycle

Polling protocols typically operate in cyclic basis, with each ONU polled once per cycle and allocated a transmission window based on its demand. The maximum cycle duration ($C_{\max}$) is related to the maximum transmission windows (set by the OLT) for N ONUs by

$$C_{\max} = \sum_{i=1}^{N} W_{i,\max} + NT_g \quad (2)$$

where T_g is a guard interval between successive ONU transmissions. The cycle duration actually changes with the dynamics of the upstream traffic. Under light traffic loads, the cycle duration reduces to much less than $C_{\max}$, which has the effect of giving ONUs in demand more bandwidth than guaranteed and thereby reducing their average packet delays. However, the polling cycle cannot be less than the maximum RTT. This is simply because each polling table entry should be updated within the OLT before issuing a grant to the corresponding ONU. Under heavy traffic, the cycle duration approaches its maximum, giving ONUs their minimum guaranteed bandwidths. We therefore define the *effective cycle duration* (C_{eff}) to be the sum of the granted transmission windows within a cycle

$$C_{\text{eff}} = \sum_{i=1}^{N} W_i + NT_g \le C_{\max}. \quad (3)$$

This expression is in fact ideal, assuming no idle gaps in the cycle other than guard intervals. This is not always true, since the OLT may sometimes pause and wait for a report that has not yet arrived. Thus, C_{eff} corresponds to the network load, but is lower bounded by the maximum RTT.

B. Centralized Polling Delays

Fig. 3 illustrates the different types of delays a packet may experience in a centralized polling scheme, from the time of its arrival till the time of its transmission; *reporting*, *grant*, and *queuing* delays, which we refer to as *pre-transmission* delays.

1) Reporting Delay: A report message is sent once per cycle when the ONU is polled. A packet, therefore, experiences a reporting delay, which may be zero, if the packet arrives right before sending a report, or a whole cycle, if the packet had just missed the report. The average reporting delay is thus half the average cycle duration ($C_{\text{avg}}/2$).

2) Grant Delay: After the packet is reported, it may wait multiple cycles before being transmitted, depending on both the buffer occupancy and the size of the transmission window. At best, the packet waits until the ONU is granted transmission in the following cycle, which is at least one RTT. The network reach is, therefore, reflected in grant delays.

3) Queuing Delay: When an ONU finally receives a grant message, it starts transmitting packets one after another within its granted window. Packets, therefore, experience queuing delays proportional to their queue positions.

Once packet transmission starts, two more delays are introduced: *transmission* and *propagation* delays. While pre-transmission delays relate to the DBA algorithm, the other two delays depend on the network reach, rate, and packet lengths, regardless of the algorithm. Thus, the main objective of any DBA scheme is to reduce pre-transmission delays. It can be seen, however, that centralized grant delays contain both transmission and propagation delays, making centralized pre-transmission delays also sensitive to and affected by extending the network reach. The increased propagation delays of LR-PONs increase the DBA response time and result in increased delays. Fig. 4 illustrates the performance degradation in both pre-transmission delays and total delays of IPACT due to extending the network reach. Using simulations at various distances, the average pre-transmission delays are shown to be always above 1.5RTT, whereas total delays are above twice the RTT. Although the exact nature and extent of the performance degradation depends on the employed DBA algorithm, most centralized polling algorithms will have the same lower bounds. For instance, multithread polling, proposed as a solution for LR-PON, is shown in [10] to have pre-transmission delays also above 1.5RTT. Its performance is, thus, still affected by the network reach. The only case polling schemes may break such lower bounds is when ONUs are given extra credit, allowing new packets to be transmitted without being reported. The sizes of credits can be fixed, proportional to reports, or more efficiently determined using traffic prediction as discussed below.

C. Centralized Polling With Traffic Prediction

Queue size prediction can be employed to estimate the traffic buffered in each ONU from the time its report was sent till the beginning of its next transmission. In [15], IPACT is combined with such an estimation algorithm that is based on the self-similarity characteristics of network traffic. The amount of packets arriving between two successive pollings is estimated in each

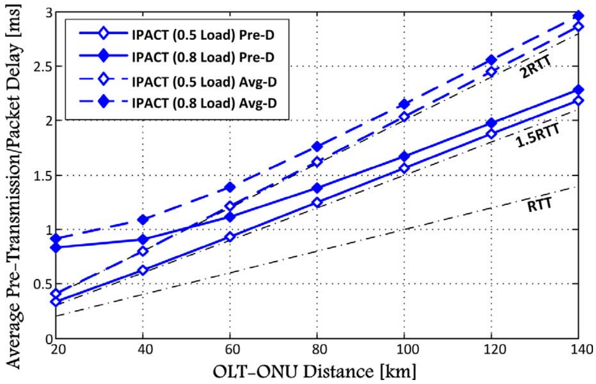

Fig. 4. Degradation of centralized DBA due to PON extension.

ONU, by observing the arrival rate for a short duration ΔT and multiplying it with its locally measured cycle duration. Each ONU then reports this estimation to the OLT together with its buffer report. The OLT considers this estimation when granting the ONU in the next cycle as

$$W_i = \min(R_i + \alpha E_i, W_{i,\max}) \tag{4}$$

where E_i is the estimated amount of packets for ONU_i and α is an estimation factor used to adjust the impact of the estimation on the grant size. Ideally, if the amount of newly arriving packets is accurately estimated, all buffered packets may be granted and the next buffer report will be zero. In this case, the next ONU grant size will only be determined using the estimation.

Predictive schemes may be able to alleviate the degraded performance of LR-PONs to a certain extent. However, since access traffic is neither homogeneous nor continuous, prediction errors will underutilize the upstream channel and impose unnecessary packet delays. In this paper, we also compare our proposed scheme with the grant-estimation (GE) algorithm described, which was proven to be better than other predictive algorithms [15].

III. Decentralized Media Access

Decentralized schemes have been proposed before for traditional PONs. Some schemes were contention based that do not ensure bandwidth guarantees [18], [19], while others for instance aimed to support offline DBA without imposing idle periods as the case with centralized offline scheduling [13]. Most of these schemes required a fully broadcasting PON that causes significant upstream power loss. Generally, decentralized schemes did not find much acceptance, either for not showing much improvement over centralized schemes, or for requiring special architectures. However, decentralized schemes may now show significant improvement over centralized schemes with ONUs located very far from the CO.

As the network reach is extended, it is no longer appropriate for ONUs to report their buffer status and wait for grants from the CO. Instead, the ONUs themselves should decide when to send data and for how long, thus allowing packets to transmit much sooner. However, to support bandwidth guarantees, ONUs must communicate together to coordinate their transmissions. Moreover, a fully decentralized scheme does not support centralized control necessary for managing bandwidth allocation according to user SLAs. In [20], we proposed a decentralized scheme that, at the same time, maintains centralized operator control. In the proposed scheme, ONUs basically take turns transmitting in a round robin fashion according to a predefined sequence. This is equivalent to an online DBA scheme that is both simple and does not make ONUs wait for a global decision. To ensure that an ONU does not monopolize the upstream channel, each ONU decides how much it will send (according to its buffer) without exceeding a certain maximum. Such a scheme operates on cyclic basis with an adaptive cycle proportionate to the sizes of upstream transmissions. We, therefore, call this scheme *Taking Turns with Adaptive Cycle Time* (TTACT).

A. Acquiring Communication Between ONUs

In order to efficiently utilize the upstream channel, an ONU that is scheduled next must start its transmission such that it arrives at the OLT right after its preceding ONU's transmission. The ONUs could be made to sense each other's transmissions using the *optical loop-back* technique, in which the 1: N SC is replaced with a 3: N coupler with two ports connected together through an isolator [13]. This causes portion of the upstream signal power to reflect back and broadcast to all ONUs, which may enable each ONU to monitor the upstream channel and detect the end of transmission of its preceding ONU. However, idle gaps will occur depending on the distances between the ONUs. The technique may also be unattractive for LR-PONs since the upstream power loss may place boundaries on the network reach or the splitting ratio.

Another way would be for an ONU to receive a message from the preceding ONU declaring its transmission size so that the following ONU knows when to start. For that we propose using out-of-band (OOB) communication on a control wavelength (e.g., U-band reserved for monitoring) to manage media access [20]. This wavelength will be reflected back by either attaching a fiber Bragg grating (FBG) or by using a bandpass filter combined with a 2: N coupler, as shown in Fig. 5(a). Using this wavelength, each ONU sends a very short time-stamped frame at the beginning of its transmission, as illustrated in Fig. 5(b), announcing how many bytes it intends to send. Upon receiving the frame, the following ONU schedules its transmission such that it arrives at the OLT right after the current transmission leaving a small guard interval. This scheduling is done using the frame timestamp together with a local time reference achieved by OLT's broadcasting transmissions. The chances of intertransmission gaps are reduced in this scheme, since the time it takes for the frame to reach the following ONU on the control channel will be during ongoing upstream transmission. Therefore, an ONU in TTACT grants the following ONU media access by reporting to it the length of its transmission window. This, however, requires additional transceivers to be placed in ONUs [20].

In this paper, we propose two alternative techniques that avoid using additional transceivers. The first is using subcarrier multiplexing to transmit both data and control messages using a single laser. The control information, carried by a low-bandwidth subcarrier, is electrically multiplexed with the baseband data before modulation. In this case, the FBG waveband reflector attached to the coupler will be designed to only reflect the control subcarrier. For ONUs to receive this subcarrier, either additional receivers are installed or wide downstream receivers are accompanied with two electrical bandpass filters:

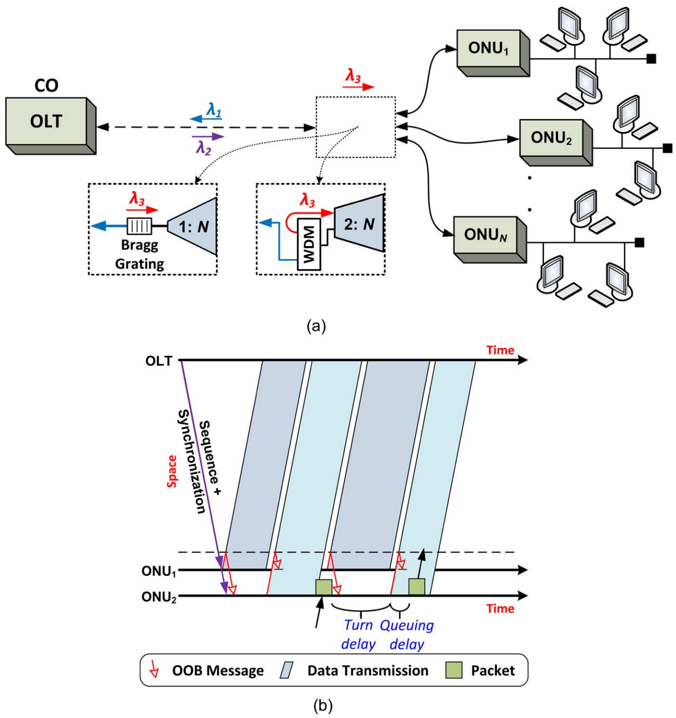

Fig. 5. OOB loop-back technique using a wavelength reflector. (a) Architecture. (b) Space-time diagram.

one for the downstream data signal and another for the control subcarrier. The principle described here comes with its own drawbacks, and experimental demonstrations are to be done in the future to assess about its feasibility.

The second technique completely avoids the requirement for the control wavelength by sending control frames on the upstream wavelength itself, at the beginning of ONU transmissions, and receiving them on the downstream wavelength without them having to go through the OLT. This could be done by placing a powered layer-2 forwarding device in the RN/LX in order to read out control frames and send them back to ONUs. This requires incorporating a buffer within the device allowing it to momentarily pause (store and forward) the OLT's downstream transmission for almost 0.5 μs to inject a control frame. The idea of placing a layer-2 forwarding device in the RN of an LR-PON has also been proposed in [21] under different context. Fig. 6 illustrates a remote node MAC-forwarding block diagram built on top of a repeater to support communication between ONUs by filtering and forwarding network traffic appropriately. Both downstream and upstream frames are initially buffered until they are classified by reading up to 64 bytes of each frame header (including the destination MAC-address and logical-link identification unique for each ONU). This is enough to determine the destination of an upstream frame to either redirect it back or forward it to the OLT. The header reading process is also crucial in identifying connected ONUs and updating the forwarding table [21]. After the forwarding decision has been made, both OLT control frames and redirected upstream control frames are queued into a high-priority buffer to be transmitted as soon as possible. This technique will have almost the same performance as the OOB technique, except that the looping back will be at the edge of the access area.

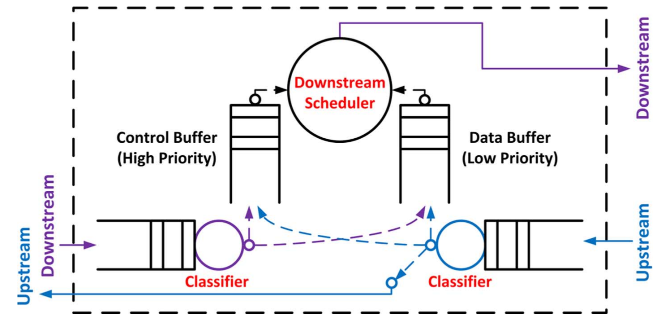

Fig. 6. Remote node MAC-forwarding block diagram.

B. Decentralized Cycle Duration and Delays

Unlike centralized schemes, the cycle duration here is completely independent of the RTT, with pre-transmission delays independent of the distances between the OLT and ONUs, but rather dependent upon the ONUs distances from the reflector (whether it is the OOB loop-back or the MAC-forwarding device). The cycle duration cannot be less than the time it takes for all ONUs to take turns, which is the time it takes a control message to travel from each ONU to the reflector and back to the following ONU:

$$C_{\min} = \sum_{i=1}^{N} \frac{2L_{\mathrm{ONU}_i}}{S} + N\frac{l}{R} \tag{5}$$

where $L_{\mathrm{ONU}i}$ is ONU_i's distance from the reflector, S is the speed of light in the fiber, l is the frame length, and R is the transmission rate. It is expected that the decentralized scheme will show significant improvement in the delay performance over a centralized scheme when the cycle is shorter than the centralized minimum cycle (RTT). In fact, the decentralized scheme can still perform better even with longer cycle durations, since a packet is sent as soon as possible without having to wait for a grant in a future cycle.

Fig. 5(b) illustrates the different types of delays in the proposed decentralized scheme: *turn* and *queuing* delays. The turn delay can be defined as the time a packet has to wait till its ONU's turn to transmit. The packet may have to wait multiple cycles (ONU turns) before being transmitted, depending on both the buffer occupancy and the size of the ONU transmission window.

C. Centralized Operator Control

Operator control over the network is necessary to manage bandwidth allocation and quality of service (QoS) according to user SLAs. To maintain centralized control over the proposed scheme, ONUs occasionally receive control parameters from the OLT upon an ONU initialization or a change of an SLA. These parameters control how ONUs transmit by specifying their transmission sequence, the maximum transmission window for each ONU, and its QoS parameters. The key feature of our scheme is that ONUs do not have to wait for these parameters to transmit, since the parameters do not allocate bandwidth, but merely supervise upstream media access. The ONUs are to be designed to operate on default parameter values or the 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

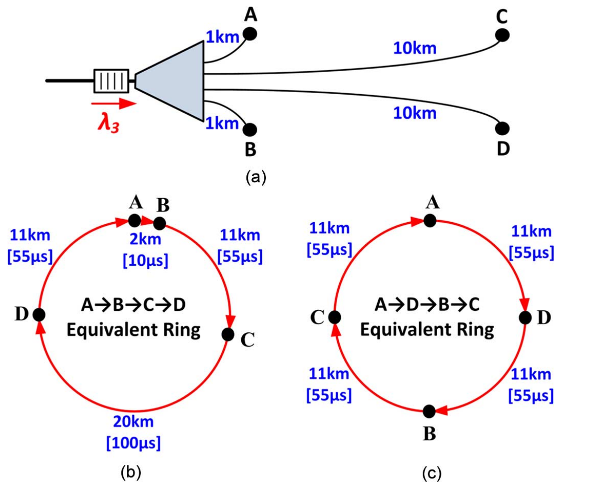

Fig. 7. Sequence effect on propagation distances between ONUs. (a) Nearest-to-farthest equivalent ring. (b) Statically optimized equivalent ring.

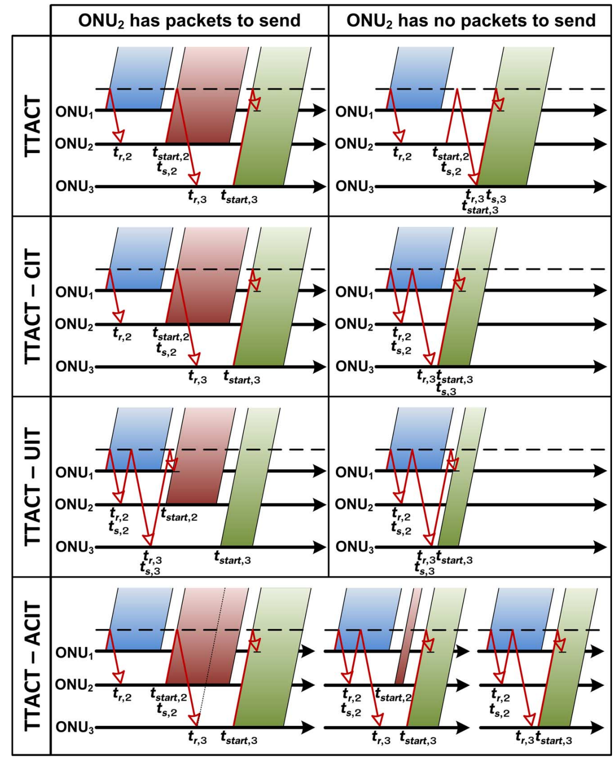

Fig. 8. Different ONU tagging schemes.

each ONU's window size and its timing, are now locally managed between ONUs.

IV. Enhancing TTACT

Upstream idle periods may often occur in TTACT when an ONU has nothing to transmit. In that case, the following ONU will immediately start transmitting upon receiving the control message from the preceding ONU, which takes time depending on the propagation distance between the two ONUs, and results in an idle period of

$$T_{\text{idle}} = T_g + l/R_{\text{OOB}} + 2L_{\text{ONU}_{i+1}}/S \tag{6}$$

In this section, we propose various new schemes to minimize and completely eliminate idle periods on the upstream channel when an ONU has little or nothing to send. First, we study altering the transmission sequence. Next, we propose a different approach, in which we accelerate the OOB signaling between ONUs. We also consider how unused bandwidth from lightly loaded ONUs can be distributed among ONUs in such an online scheme.

A. Transmission Sequence

The ONUs' transmission sequence can be set to minimize propagation distances between the ONUs. This is well demonstrated when distances between the reflector and ONUs vary widely. For example, in Fig. 7(a), we consider the OOB loopback technique with four ONUs: two are close to the FBG and the other two are 10 km away. Fig. 7(b) illustrates the equivalent ring of the OOB propagation between the ONUs when the sequence is set from nearest to farthest. The greatest propagation distance lies between the two distant ONUs (C and D). Therefore, if the first distant ONU (C) does not have data to send, a long upstream idle period will take place until the control message reaches the following ONU (D). Fig. 7(c) illustrates a different case, in which each distant ONU follows a close one. This helps reducing long propagations between subsequent ONUs. Therefore, with all ONUs active, a *statically optimum sequence* (SOS) can be set corresponding to ONUs' distances from the reflector. The sequence may also be made to adapt to network traffic. For example, if a given ONU continues to have nothing to transmit for consecutive cycles, it can be taken out of the sequence for a number of cycles. This will significantly shorten the cycle duration and improve upstream utilization. This will be a topic of a future study.

B. Immediate Tagging

When the OOB technique is used for communication between ONUs, control messages on the control wavelength can be accelerated to reduce and even eliminate chances of long idle periods when an ONU has nothing or too little to send. This is driven from the fact that an ONU may usually receive a control message long before it starts to transmit. We define $t_{\text{start},i}$ as the time ONU_i starts its data transmission, whereas $t_{r,i}$ and $t_{s,i}$ are the times it receives an OOB control message (gets tagged) and the time it sends its OOB message (tags the following ONU), respectively.

Fig. 8 illustrates several proposed signaling (tagging) schemes showing how they can mitigate idle periods. Each scheme is typically shown for two cases; when ONU_2 does and does not have packets to send at time $t_{r,2}$.

1) Conditional Immediate Tagging (CIT): Unlike the basic TTACT scheme, an ONU here does not always send its control message at the beginning of its transmission. If the buffer is empty at time $t_{r,i}$, the ONU immediately tags the following ONU giving up its turn within the current cycle:

$$t_{s,i} = \begin{cases} t_{r,i} & \text{if BUF}\,(t_{r,i}) = 0 \\ t_{\text{start},i} & \text{otherwise.} \end{cases} \tag{7}$$

2) Unconditional Immediate Tagging (UIT): In this scheme an ONU immediately tags the following ONU indicating how

much it will send regardless of its buffer status ($t_{s,i} = t_{r,i}$). Thus, the ONU will only send reported packets even if more packets had arrived before its start of transmission.

3) Aware Conditional Immediate Tagging (ACIT): Here, the only case an ONU may not immediately tag the following ONU, upon getting tagged, is when it has enough packets to utilize the propagation distance to the following ONU:

$$t_{s,i} = \begin{cases} t_{\text{start},i} & \text{if } W_i(t_{r,i}) \geq l/R_{\text{OOB}} + 2L_{\text{ONU}_{i+1}}/S - T_g \\ t_{r,i} & \text{otherwise.} \end{cases} \quad (8)$$

This ensures that when the ONU sends the control message at the start of its transmission (as in basic TTACT), the time it will take it to reach the following ONU will be completely utilized on the upstream channel. The ONU can, therefore, accommodate packets arriving between the time it received a control message ($t_{r,i}$) and the time it sends one ($t_{s,i}$). This scheme requires each ONU to be aware of the propagation distance to the following ONU.

C. Excess Distribution

In centralized offline DBA with excess distribution, ONUs are partitioned into two groups: *normally loaded* and *overloaded*. Normally loaded ONUs are those with a report size less than or equal to their maximum window size ($R_i \leq W_{i,\max}$), while overloaded ONUs are those whose report size is larger ($R_i > W_{i,\max}$). After all report messages are collected, excess bandwidth left over from normally loaded ONUs can be distributed among overloaded ONUs [9]. To carry out something similar in a decentralized online scheme, each ONU could be allowed to observe the previous $N-1$ transmissions and use any of the cycle's accumulated excess. This is an attempt to get rid of the fixed maximum window limit, since the window may reach the maximum cycle duration $C_{\max}$ if only one ONU has data to send. We aptly call this scheme *usable cycle excess* (UCE) and could be viewed as a decentralized version of the elastic service introduced in [14].

V. Simulation Results

In this section, we first compare the performance of the proposed decentralized scheme TTACT with its centralized counterpart. We next show how it gains more advantage as the network is extended. Finally, we study how the enhancement schemes discussed in Section IV may add to the performance. In our study, we consider a 100 km LR-PON consisting of an OLT and 16 ONUs. The ONUs share an upstream wavelength of 1 Gb/s, whereas from the access side, end users have an access rate of 100 Mb/s. The system throughput is, therefore, less than the peak aggregated load from all ONUs. Each ONU has a 10 MB buffer, and the traffic used is self-similar Ethernet traffic with a Hurst parameter of 0.8. We also take into consideration the 12-byte interframe gaps and 8-byte preambles ahead of each Ethernet frame. The maximum cycle ($C_{\max}$) is set to 5 ms, which is found to be convenient for centralized and decentralized schemes at a 100 km span, and T_g is set to 5 μs [14].

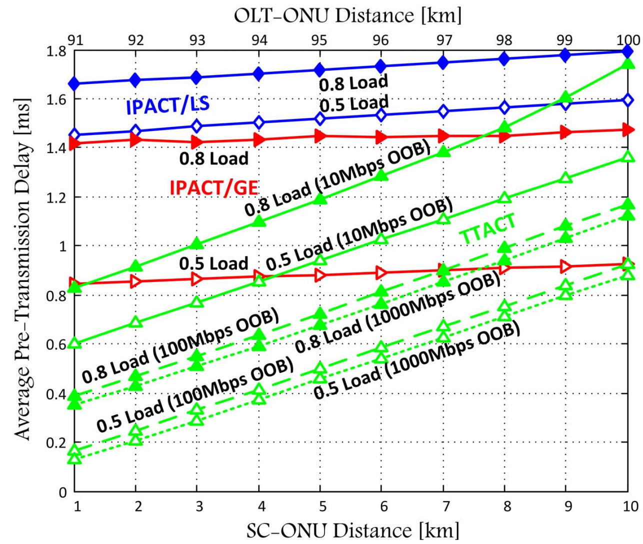

Fig. 9. SC-ONU distance extension effect on delays.

For IPACT with GE, we set ΔT to 1 ms [15], and we find setting α to 0.75 achieves an optimum performance. For our proposed decentralized scheme, we consider the OOB technique, which enables using the immediate tagging schemes. The location of the SC is essential in the study as the reflector is considered attached to it, and we designate ONU_i's distance from it as $L_{\text{SC,ONUi}}$. We assume two possible locations for the SC: either 90 or 95 km away from the OLT. The 90 km scenario is the worst case for our approach, since the reflector is at the beginning of the drop section making the furthest ONU possibly 10 km away. The 95 km scenario is more convenient since the reflector is in the middle of the drop section, making the farthest ONU only 5 km away.

A. Performance Within a 100 km LR-PON

The cycle duration of the proposed decentralized scheme is affected by both the ONUs' distances from the reflector and the OOB transmission rate (5). To show how the scheme performs under the worst case, we maximize the distance between the SC (with the attached reflector) and the ONUs. We also simulate the scheme with different OOB rates (10, 100, and 1000 Mb/s). Fig. 9 presents a general overview of average pre-transmission delays of centralized IPACT and decentralized TTACT, as the ONUs are moved further from the SC and deeper into the 10 km drop section. Although, TTACT's performance is degraded, especially when using a low OOB rate, it still performs better than the centralized schemes when using 100–1000 Mb/s OOB rates. Since using a 1000 Mb/s rate does not add significant improvement over using a 100 Mb/s rate, we find the latter rate sufficient to carry the OOB control messages and will thereby decrease the costs of the transceivers.

Fig. 10 offers more insight on the effect of increasing ONU distances from the SC. For clarity, we only show the effect on both IPACT with LS and TTACT when using a 100 Mb/s OOB rate. In addition to the pre-transmission delay curves D_{pre}, we also show their corresponding average effective cycles (dashed) and the minimum cycle (heavy dotted). Recall that the cycle

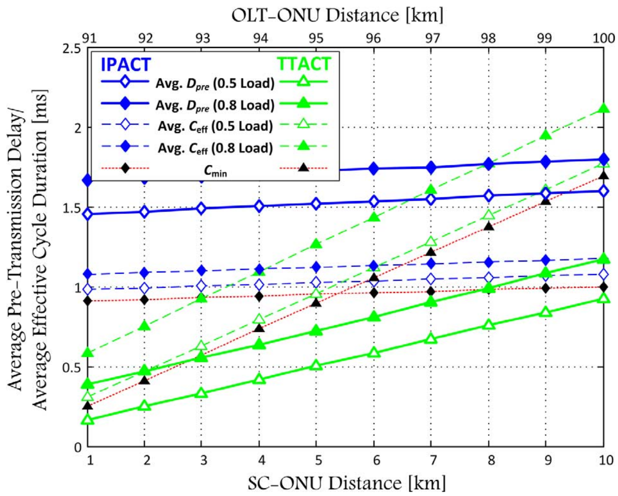

Fig. 10. SC-ONU distance extension effect on delays and cycle durations of both IPACT and TTACT with 100 Mb/s OOB rate.

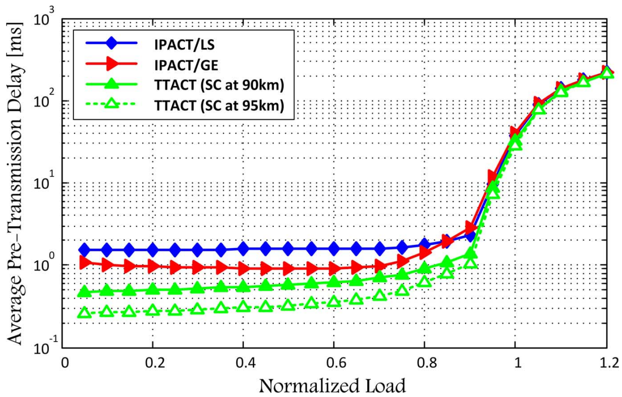

Fig. 11. Average pre-transmission delay comparison.

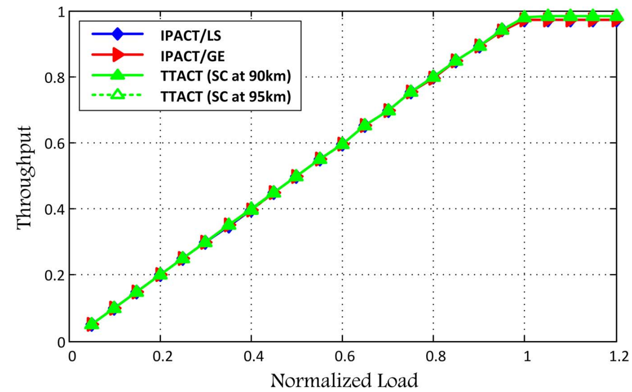

Fig. 12. Throughput comparison.

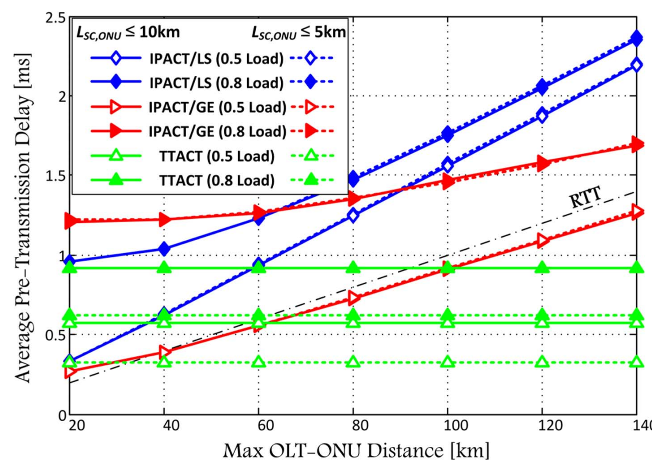

Fig. 13. Effect of extending the network reach on predelays.

durations and delays of a centralized DBA are affected by the ONUs distance from the OLT (top axis). This explains the slight increase in delay and cycle durations, since the 9 km increment only affects the RTT by 9%. On the other hand, the delays and cycle durations of the decentralized scheme are affected by the distance from the SC (bottom axis). Therefore, the 9 km increment increases the minimum cycle from 0.25 to 1.7 ms, becoming nearly 60% greater than that of IPACT. However, TTACT's delays remain much lower, which shows how delays do not relate to the cycle duration alone, but their nature is another factor. In IPACT, a packet waits till it is first reported then granted, making it wait at least one cycle, whereas it may be directly transmitted in the current cycle of the decentralized scheme. This is why decentralized delays do not increase with the same slope as that of their cycle durations, unlike IPACT. As the ONUs are moved closer to the SC, the reduction of average delays is found to range from about 30% to 75% at 0.8 network load, which is equivalent to 25% to 60% reduction in total average delays (including transmission and propagation delays). If the SC is to be placed at the middle of the drop section (95 km from the OLT), TTACT's curves along with the bottom axis will shift to the right, and start in line with 96 km of the top axis, instead of 91 km, resulting in an improvement ranging from about 60% to 75% (45% to 62% reduction in total delays).

A full comparison of average pre-transmission delays of IPACT with those of TTACT is shown in Fig. 11, when the SC is placed either at 90 or 95 km away from the OLT. The ONUs here are placed randomly in the drop section to make a practical case. Although using traffic prediction succeeds in decreasing the delays of IPACT under light and moderate loads, it performs worse under heavy loads. Decentralized TTACT, on the other hand, shows significant improvement, with more than 65% reduction in delays of IPACT with LS at normally loaded conditions (more than 50% reduction in total delays). A throughput comparison is also shown in Fig. 12. IPACT's maximum throughput is found to be 97.2% for LS and 97.1% for GE, whereas TTACT achieves a maximum of 97.8% and 98.1%, when the SC is located at 90 and 95 km from the OLT, respectively.

B. Performance Advantage With Network Extension

Fig. 13 shows the effect of extending the network reach on packet pre-transmission delays of all schemes, when ONUs are placed randomly but no further than 5 or 10 km from the SC. Changing the SC location hardly affects the delays of centralized schemes. Although using traffic prediction succeeds in breaking the delay lower bounds of centralized polling schemes, especially under light loads, the performance is still affected by the network extension. On the other hand, the pre-transmission delays of the decentralized scheme are

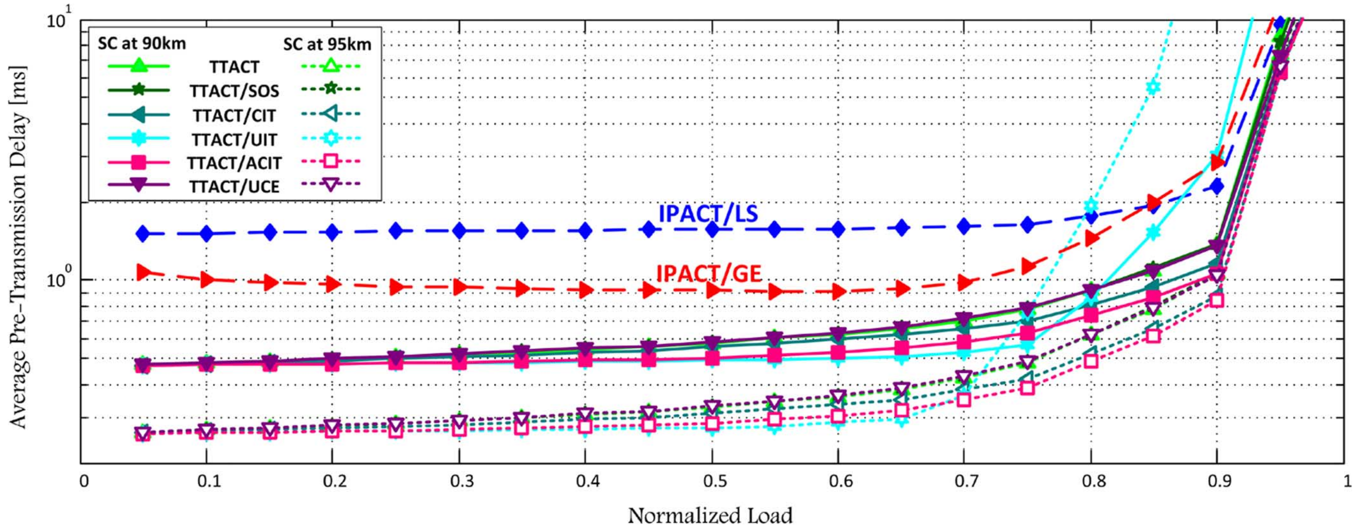

Fig. 14. Average pre-transmission delays of decentralized enhancement schemes.

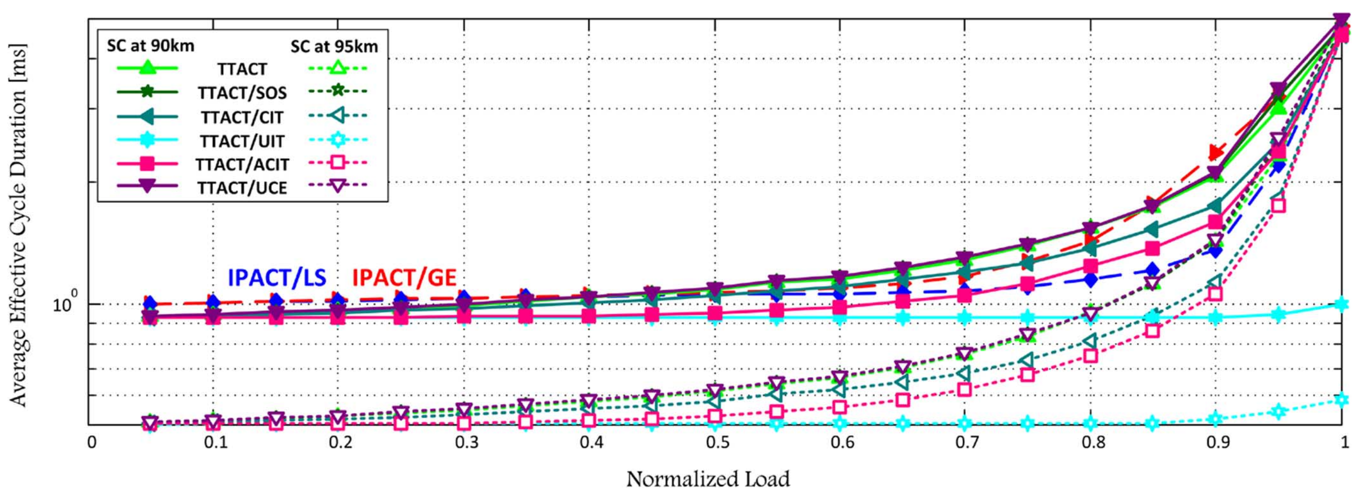

Fig. 15. Average effective cycle durations of decentralized enhancement schemes.

completely unaffected by extending the network reach. In fact, the scheme gains more advantage with network extension, and its pre-transmission delays eventually become lower than the RTT.

C. Enhancement Schemes

A comparison of average pre-transmission delays of the proposed enhancement schemes is shown in Fig. 14 at different network loads when the SC is placed at 90 and 95 km away from the OLT. The delay patterns are shown to almost repeat themselves for both SC locations. Under light loads, the enhancement schemes do not show much improvement over TTACT. However, both UIT and ACIT show around 10% improvement at 30% load. UIT shows more improvement than ACIT before it starts to degrade at 85% load, when the SC is at 90 km, and at 70% load, when the SC is at 95 km. At these loads, ACIT achieves more than 20% improvement. CIT also shows improvement over TTACT, but not as much as ACIT. Using TTACT with SOS or UCE does not show significant improvement except at loads greater than 90% and 95%. Using SOS shows to have slightly less delays, whereas using UCE shows to be a little better, since it allows the ONUs to use excess at high loads.

The behavior of these enhancement techniques can be explained by studying their effective cycle durations shown in Fig. 15. Although the cycle durations of the decentralized schemes exceed that of IPACT when the SC is at 90 km, their delays are still less than IPACT. UIT clearly has the shortest cycle since an ONU immediately reports its buffer status. It shows the greatest performance under light loads as it completely eliminates long idle periods. However, its accelerated signaling makes the cycle too short under heavy loads forcing more packets to wait for future cycles. Since ACIT is actually a compromise between UIT and CIT, it has the second shortest cycle. It performs well under light loads and also allows the cycle to extend more flexibly under heavy loads, thus achieving the overall best performance (more than 80% improvement over IPACT/LS at loads $\leq$80% when the SC is at 95 km). As for UCE and SOS, both appear to have slightly longer cycles than basic TTACT. This is accompanied by a slight decrease in their delays (see Fig. 14), indicating that the increase in cycle durations allows packets to be sent sooner. However, the cycles of both are not fully utilized and still have idle periods since

immediate tagging schemes achieve lower delays at shorter cycles.

VI. Conclusion

In this paper, we addressed the problem of bandwidth allocation in LR-PON. We proposed an online decentralized media access scheme to remedy the effect of the long CO-to-users control loop that degrades the performance of centralized allocation. In our proposed scheme, we enable communication between ONUs to manage media access without causing upstream power loss. We also maintain centralized operator control to manage and support service differentiation according to user agreements. Moreover, we studied different enhancement approaches, two of which aimed to mitigate intertransmission idle periods, when an ONU has little or nothing to send, by setting the ONUs' transmission sequence to minimize propagation delays and accelerating the OOB signaling between ONUs. The third approach allowed using the accumulated bandwidth excess.

Numerical results show that the proposed decentralized scheme can reduce average upstream pre-transmission delays below those of its centralized counterpart by more than 75% at normal loads when the SC is placed in the middle of the drop section, while also maintaining high throughput. This improvement is mainly due to the delays' independence of the ONUs distances from the OLT, and their dependence on their distances from the coupler, thus leading to more performance gain as the feeder reach is extended. Furthermore, accelerating the signaling between ONUs was proven to be the most promising enhancement approach, reducing pre-transmission delays by more than 80% under normal loads (60% reduction in total delays).

Acknowledgment

The authors would like to thank the reviewers for their constructive feedback that considerably improved the quality of this paper.

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