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# Taking Turns with Adaptive Cycle Time and Immediate Tagging

## A Decentralized Upstream Media Access Scheme for Long-Reach PON

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***Abstract*—Several centralized algorithms have been proposed for bandwidth-allocation in passive optical networks (PONs); making the optical line terminal (OLT) in the central office the intelligent device that arbitrates time-division access to the shared upstream channel. When the distance between the OLT and optical network units (ONUs) is extended from 20 km to 100 km and beyond, as suggested by next generation long-reach PONs, it becomes difficult for centralized algorithms to maintain their performance and to support service differentiation for real-time applications. This is because these algorithms are based on bandwidth negotiation messages frequently exchanged between the OLT and ONUs, which become seriously delayed, thereby delaying packet transmissions and causing the performance to degrade. Decentralized schemes, on the other hand, are independent of the OLT distance and can perform better with such extended reach. In this paper, we introduce and enhance the performance of a decentralized scheme for the emerging LR-PON. Simulation results show that the proposed scheme can significantly reduce upstream packet delays below those of centralized algorithms by 80% while keeping a high throughput.**

***Keywords-decentralized media access; Ethernet; long-reach passive optical network (LR-PON); optical access network.***

## I. INTRODUCTION

Passive optical networks (PONs) seem to be a promising solution to the "last mile" bandwidth bottleneck exacerbating from the increasing demand over emerging and expanding Internet services. Compared to other access technologies, PONs provide higher bandwidths at relatively lower costs. With PONs' widespread deployment all over the globe [1], research focus has shifted to their scalability with longer reach and higher split ratios. Extending the reach of the network is thought to reduce the number of central office (CO) premises located close to the customers, allowing the network operators to consolidate multiple COs in more conveniently located facilities. Higher split ratios lead to sharing the optical line terminal (OLT) and the feeder fiber among a larger number of users. The concept of long-reach PON (LR-PON) was thus proposed as a more cost-effective solution for broadband optical access networks [2, 3]. By exploiting both optical amplifiers and wavelength-division multiplexing (WDM), a LR-PON may extend the coverage of PON from the traditional 20 km to 100 km and beyond while being capable of increasing the split ratio from 64 up to 1024 and more. By extending the geographic coverage, LR-PONs can combine both access and metro networks into a single integrated system.

Many architectures were proposed for LR-PON, of which most can be categorized under 'ring-and-spur' and 'tree-and-branch' architectures [3], depending on whether the feeder (CO connection to the access areas) is a long trunk fiber or a WDM ring, as shown in Fig. 1. In both architectures, several PONs are served by a single CO. Most demonstrations put the optical network units (ONUs) within a 10 km drop section from the local exchange [3]. Despite the various LR-PONs architectures, the logical connection between the OLT and ONUs remains the same but with the distance between them extended. As illustrated in Fig. 2, all downstream transmissions are done in broadcast-basis, since it is a point-to-multipoint network. In the upstream direction, the network is a multipoint-to-point network; all ONUs transmit toward one OLT through a common passive star coupler (SC). Some media access control mechanism in the upstream direction is thus required to fairly coordinate the ONUs' transmissions and avoid data collisions.

Time-division multiple access (TDMA) has been adopted in PON standards. Centralized dynamic bandwidth allocation (DBA) schemes have been commonly used, making the OLT arbitrate time division access on the shared upstream channel by assigning different timeslots for each user [4]. The delay performance in such schemes is affected by an ONU's round-trip time (RTT) since it imposes a delay on the CO-ONU control loop. As the RTT may grow from today's 0.2ms to 1ms, the performance of centralized allocation schemes is highly degraded. The reach extension accompanied with LR-PONs therefore introduces challenges to the medium access control layer and is considered one of many research challenges facing LR-PONs [3]. In this paper, we focus on the bandwidth allocation problem under the increased propagation delays between the OLT and ONUs. We propose decentralized media access solutions and show how they are independent of the RTT and therefore better suited for LR-PONs.

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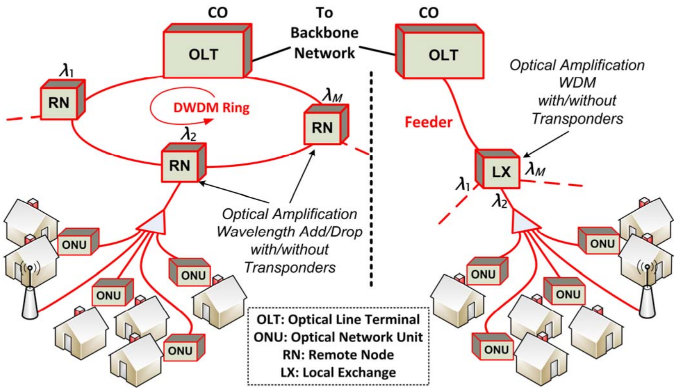



Figure 1. Basic LR-PON architectures: ring-and-spur (left) and tree-and-branch (right).

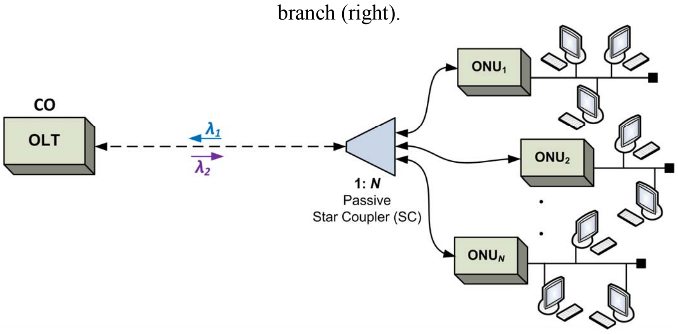



Figure 2. Logical connection between OLT and ONUs in a LR-PON.

The rest of this paper is organized as follows. In Section II we briefly review the basis of centralized bandwidth allocation, explaining how its performance is highly affected by extending the network span. Next, we introduce the principles of our decentralized scheme in Section III, discussing how its performance could be further enhanced. Section V presents numerical results and Section VI concludes the study.

## II. CENTRALIZED DYNAMIC BANDWIDTH ALLOCATION

In centralized allocation schemes, the OLT arbitrates time-division access to the shared upstream 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 defined in both EPON and GPON standards. In a polling scheme, the OLT keeps a polling table with an entry for each ONU to record both its RTT and buffer status. Each ONU sends a report message informing the OLT of the amount of its buffered data. The OLT then continuously updates its polling table, processes the reports, and polls the ONUs granting them transmission windows corresponding to their reported buffer status via grant messages. Therefore, in polling schemes, the OLT must first know the buffer load of each ONU before allocating it upstream bandwidth according to its bandwidth demand. Centralized algorithms therefore suffer from a control-plane delay caused by the propagation delays between the OLT and ONUs, which delay the exchange of the bandwidth negotiation messages.

Polling protocols operate in cyclic basis, with each ONU polled once per cycle. The maximum cycle duration ($C_{\max}$) is related to the maximum allowable transmission windows of $N$ ONUs by:

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

where $W_{i,max}$ is the maximum allowed window for ONU$_i$ and $T_g$ is the guard interval between successive ONU transmissions. The polling cycle duration changes with the dynamics of upstream traffic. Under light traffic loads, the cycle duration usually reduces to much less than $C_{\max}$, which has the effect of giving ONUs in demand more bandwidth than guaranteed, and thereby reducing the average packet delay. 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 [5]. Under heavy traffic, the cycle duration reaches its maximum giving ONUs their minimum guaranteed bandwidths. We therefore define the effective cycle duration to be the sum of the granted windows within a given cycle;

$$C_{eff} = \sum_{i=1}^{N} W_i + NT_g \leq C_{\max} \quad (2)$$

where $W_i$ is the granted window for ONU$_i$ corresponding to its buffer status reported to the OLT. Thus the polling cycle adapts to network load but is lower-bounded by the maximum RTT.

Interleaved polling with adaptive cycle time (IPACT) is a pioneer centralized algorithm for bandwidth allocation in EPON [5]. It employs a pipelined timeslot-assignment (Fig. 3), allowing the OLT to send a grant message to the next ONU before data and report messages from previously polled ONUs arrive. This is feasible since upstream and downstream channels are separated, and since the OLT maintains relevant information about each ONU in the polling table. In IPACT, the OLT employs service level agreements (SLAs) of end users to upper-bound the allocated bandwidth (window size) of each ONU. Several grant sizing schemes were investigated in [5] and the limited service discipline was found to exhibit the best performance, by which the OLT grants an ONU the number of bytes requested, but no more than a certain maximum;

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

where $R_i$ is the requested window (report) for ONU$_i$. Such a scheme assumes that no packets arrive after an ONU sends its request and therefore has the shortest cycle duration.

Fig. 3 illustrates the delays a packet experiences in centralized IPACT from the time it arrives till it is transmitted, which we refer to as *pre-transmission delays*. After a packet is reported (i.e., a report message is sent), the ONU has to wait for a grant message to start transmitting. It can easily be seen that this grant delay is dependent on the distance between the ONU and OLT, and that it increases when this distance is extended. Pre-transmission delays of centralized polling algorithms are therefore sensitive to and affected by extending the reach of the network, since the increased propagation delay leads to an increased DBA response-time that results in increased packet delays. Recent researches however addressed the problem of bandwidth allocation in LR-PON, under its increased propagation delays, by proposing new centralized bandwidth allocation schemes that are mostly based on IPACT (see for example [6] and [7]). Because they are centralized, their performance is still affected by the extended network reach and their packet delays cannot go below certain bounds. We hereby propose decentralized schemes for LR-PONs.

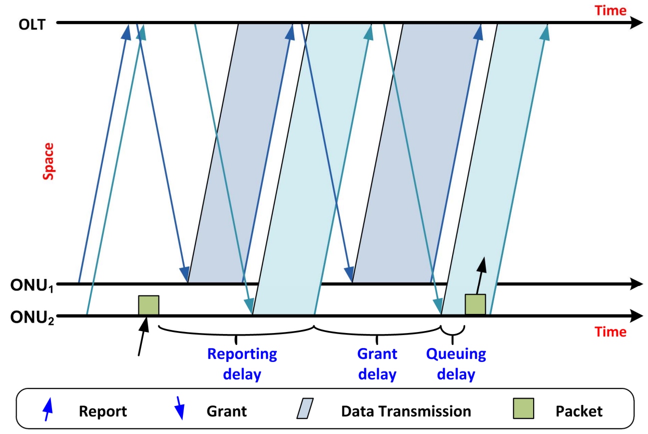


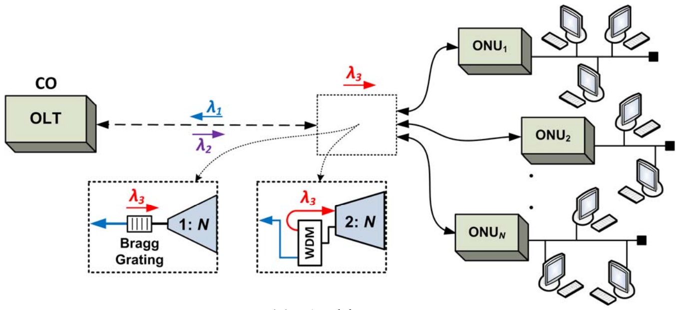

Figure 3. Delays of centralized interleaved polling.

## III. Decentralized Media Access

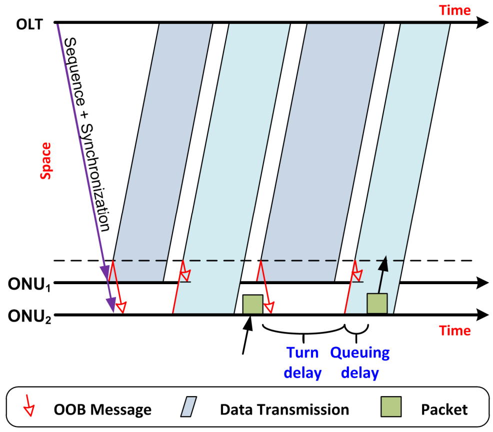
As the distance between the OLT and ONUs is extended, it will be no longer appropriate for ONUs to report their buffer status and wait for grants to transmit. ONUs themselves should decide among each other when to send data and for how long, thus making pre-transmission delays independent of the ONUs' distances from the OLT (i.e., independent of the feeder length). Such decentralized schemes can therefore show significant performance improvement over centralized schemes, especially when ONUs are located far from the CO. This comes with the cost of obtaining additional connectivity between ONUs to efficiently utilize the channel and ensure bandwidth guarantees.

Although decentralized schemes have been proposed before for traditional PONs, they did not find much acceptance, either for showing insignificant improvement over centralized schemes with such short network reaches, or for requiring special PON architectures. Moreover, most of these schemes required a full broadcasting PON design to enable ONUs to communicate or listen to each other (see for example [8]). This causes significant upstream power loss that is not attractive for LR-PONs, since it may place boundaries on the network reach or the splitting ratio. Furthermore, a fully decentralized scheme does not support centralized control necessary for managing bandwidth allocation parameters according to user SLAs.

In [9], we proposed a decentralized scheme for LR-PON that, at the same time, maintains centralized operator control. We called the scheme *Taking Turns with Adaptive Cycle Time* (TTACT). In TTACT, ONUs take turns transmitting according to a pre-defined sequence. To prevent monopolizing the upstream channel, each ONU does not transmit beyond a certain maximum in each turn. The scheme is designed to be suitable for LR-PONs with no upstream power losses, by making media access communications, between ONUs, *out-of-band* (OOB) on a dedicated wavelength (e.g. in the U-band reserved for monitoring). The wavelength is reflected back, facilitating a multipoint-to-multipoint network, using either a fiber Bragg grating attached to the SC or a wavelength filter with a 2:$N$ star coupler, as shown in Fig. 4(a). Using this wavelength, each ONU sends a very short time-stamped frame at the start of its transmission, as illustrated in Fig. 4(b), announcing how many bytes it intends to send. The frame will reach the next ONU during ongoing data transmission, thereby




(a) Architecture




(b) Space-Time diagram illustrating the different types of delays

Figure 4. OOB loop-back technique.

reducing chances of upstream idle periods caused by OOB propagation delays. Upon receiving the frame, the following ONU schedules its transmission such that it arrives at the OLT right after the current transmission, while leaving a small guard interval. This scheduling is done using both the frame timestamp together with the local time reference, achieved by the OLT's downstream broadcasting transmissions, to achieve upstream synchronization. Therefore, an ONU in TTACT grants the following ONU media access by reporting to it the length of its transmission.

The scheme also operates on a cyclic basis with adaptive cycle duration proportionate to the sizes of upstream transmissions. However, the cycle duration here and hence the delays, shown in Fig. 4(b), are independent of the ONUs distances from the OLT, but mainly dependent upon their distances from the wavelength reflector attached to the SC. The cycle duration cannot be less than the time it takes a control frame to circle through all ONUs;

$$C_{\min} = \sum_{i=1}^{N} \frac{2L_{SC,ONU_i}}{S} + N\frac{l}{R_{OOB}} \qquad (4)$$

where $L_{SC,ONUi}$ is the distance between the SC and $ONU_i$, $l$ is the frame length, and $R_{OOB}$ is the OOB transmission rate. Thus, it is expected that this scheme will show significant improvement in the delay performance when the sum of all the distances between the SC and each ONU is less than the maximum ONU distance from the OLT—when its minimum cycle becomes less than the centralized minimum cycle. In fact, it could still show improvement even with longer cycle durations, since a packet here is likely to be sent in the current cycle and does not wait for a grant in a future cycle.

### A. Centralized Operator Control

Centralized operator control is necessary to manage bandwidth allocation and service differentiation according to user SLAs. To maintain such control over the proposed decentralized scheme, ONUs occasionally receive certain parameters from the OLT that control how they take turns transmitting by specifying their transmission sequence, the maximum allowable transmission window for each ONU, and QoS parameters. The key feature of our scheme is that ONUs do not have to wait for these parameters to transmit, since they merely supervise 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. Another possible advantage of having centralized control is to take idle or faulty ONU equipment out of the transmission sequence.

### B. Immediate Tagging forEnhancing TTACT

Idle periods may exist in TTACT when a current ONU has nothing to transmit. In this case, the next ONU immediately starts transmitting upon receiving the control message. However, the time it takes the control messages to reach the ONU depends on the propagation distance between the two ONUs and results in an idle period in the upstream channel of:

$$T_{idle} = (L_{SC,ONU_i} + 2L_{SC,ONU_{i+1}})/S \qquad (5)$$

We therefore propose various signaling schemes that accelerate the signaling between ONUs, in order to mitigate the chances of long idle periods. The main idea comes from the fact that the time an ONU receives a control message is usually not the time

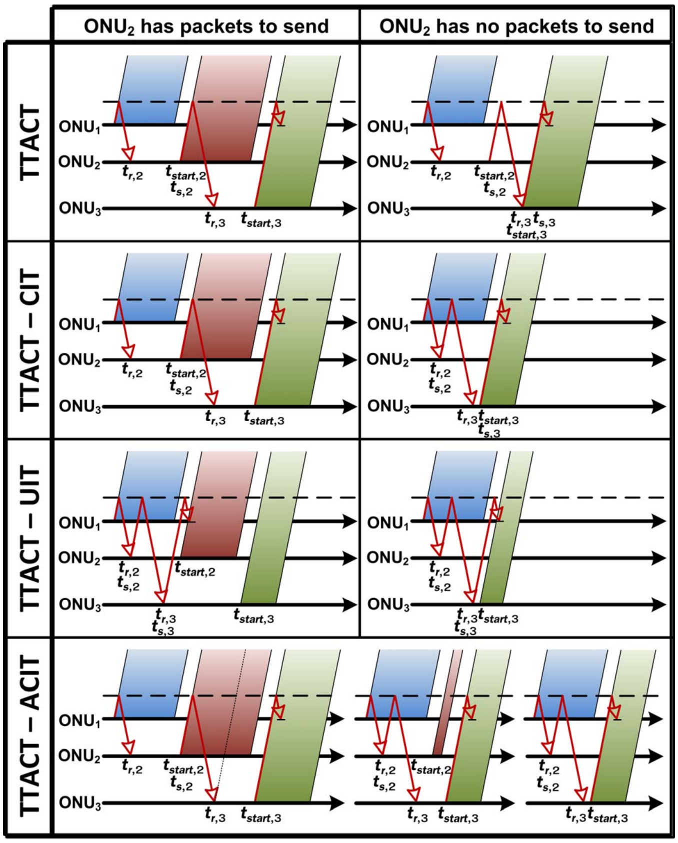



Figure 5. Different ONU tagging schemes.

it starts transmitting. First, we define the following symbols:

$t_{r,i}$: time of receiving a control message (tag) at $ONU_i$;
$t_{s,i}$: time at which $ONU_i$ sends its control message;
$t_{start,i}$: transmission start time of $ONU_i$;

Each scheme is shown in Fig. 5 in two cases; when $ONU_2$ does and does not have packets to send. Unlike the basic TTACT scheme, an ONU here will not always send the control message at the beginning of its transmission. In *conditional immediate tagging* (CIT), the ONU immediately tags the following ONU in the sequence, giving up its turn, if the buffer was empty at the time of receiving a control message ($t_{r,i}$). With *unconditional immediate tagging* (UIT), the ONU immediately sends its control message regardless of its buffer status ($t_{s,i} = t_{r,i}$). This means that the ONU will attempt to send only reported packets even if more packets had arrived before the ONU's start time of transmission ($t_{start,i}$). Finally, in the *aware conditional immediate tagging* (ACIT) scheme, the only case an ONU may not immediately send a control message upon receiving one is when the ONU has enough packets to utilize the propagation delay of the control message. This requires each ONU to be aware of the OOB propagation delay to the next ONU, which can be measured during initialization.

## IV. Simulation Results

In our study, we consider a 100 km LR-PON consisting of an OLT and 16 ONUs. The location of the passive SC is essential in the study, since the reflector is attached to it. We assume it to be placed in the middle of the drop section (i.e. 95 km away from the OLT), making the farthest ONU only 5 km away in any direction. The ONUs are placed randomly sharing an upstream wavelength of 1Gbps, whereas from the access side end-users have an access rate of 100 Mbps. Each ONU has a finite memory buffer of 10 Mbytes. The traffic used is self-similar Ethernet traffic with a 0.8 Hurst parameter. $C_{max}$ is set to 5ms for both centralized and decentralized schemes, whereas $T_g$ is set as 5µs. For our proposed schemes we use an OOB rate of 100 Mbps to lower the cost of the transceivers.

A comparison of average pre-transmission delays of the proposed decentralized schemes with those of IPACT is shown in Fig. 6 at different network loads. Decentralized TTACT shows significant improvement over IPACT, reducing the delays by more than 75% under normal loads (loads ≤ 80%). The proposed immediate tagging schemes do not show much improvement over basic TTACT at light loads. However, both UIT and ACIT show around 10% enhancement at 30% load. In fact UIT shows more improvement than ACIT before it starts to degrade at 70% load. At that load, ACIT enhances the performance by more than 20%. This behavior can be explained by studying their effective cycle durations shown in Fig. 7. UIT is shown to have the shortest cycle duration since an ONU immediately reports in all cases (Fig. 5). It therefore performs best under light loads because it completely eliminates long idle periods. However, the cycle is too short at higher loads, making more packets wait for future cycles. Since ACIT is actually a compromise between UIT and CIT, it has the second shortest cycle. It shows good performance under light loads, and allows the cycle duration to extend more flexibly at higher loads achieving the best overall performance (more than 80% improvement over IPACT at loads ≤ 80%).

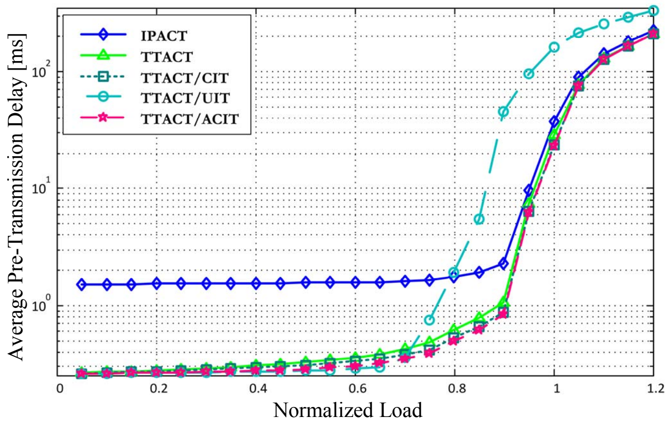



Figure 6. Average packet pre-tranmission delays in a 100 km LR-PON.

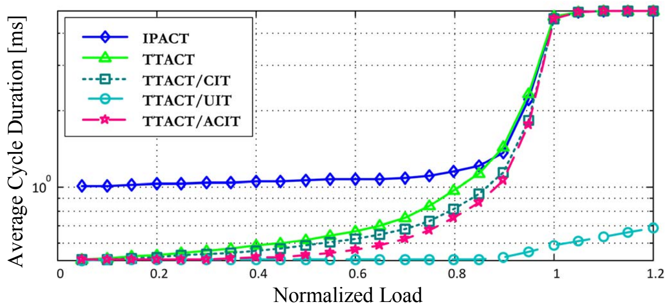



Figure 7. Average effective cycle durations in a 100 km LR-PON.

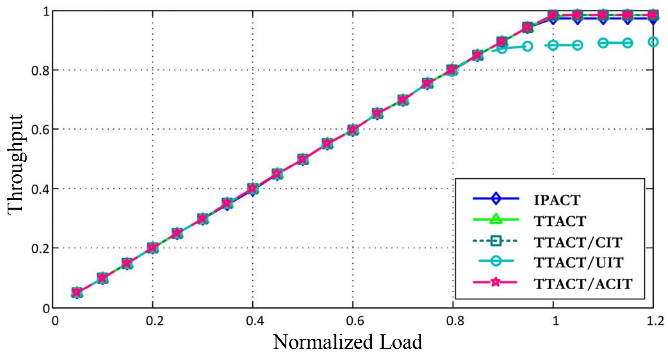



Figure 8. Normalized throughput in a 100 km LR-PON.

The throughput of the proposed schemes is compared with that of IPACT in Fig. 8. IPACT's maximum throughput is 97.2%, whereas TTACT together with CIT and ACIT achieve a maximum of 98.3%. The reason for the slight difference under heavy load is because an ONU in IPACT may be granted a timeslot smaller than requested more often, and with the OLT lacking any knowledge about the composition of its queue, the timeslot may not exactly fit a number of frames. Since Ethernet frames cannot be fragmented, an unfitting frame will be differed to the next timeslot leaving an unused remainder in the current slot and slightly degrading utilization. This does not happen in TTACT since an ONU declares to the following ONU exactly how many bytes it will send. The worst throughput is that of UIT with a maximum of 89.2%. Finally, Fig. 9 shows the effect of extending the network span on pre-transmission delays of both IPACT and TTACT showing how the latter gains more advantage as the network is extended, with its delays eventually becoming lower than the RTT.

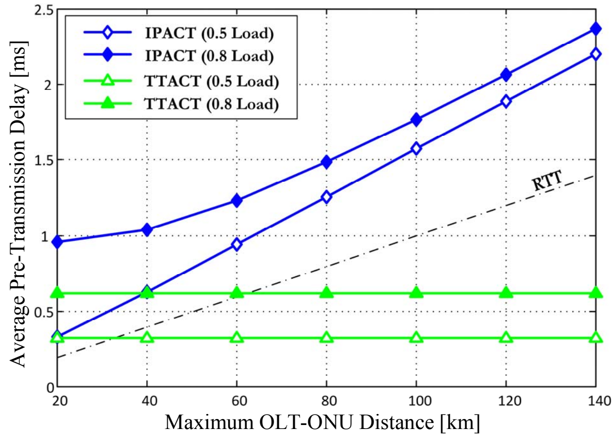



Figure 9. Network extension effect on average pre-transmission delays.

## V. Conclusion

In this paper, we addressed the problem of bandwidth allocation in LR-PON. We proposed a decentralized scheme, in which the ONUs take turns transmitting to remedy the effect of the long CO-to-users control loop. For that we suggested using out-of-band communication that allows ONUs to manage media access in a LR-PON at the expense of placing additional low rate and low cost transceivers. We maintain centralized operator control to manage bandwidth distribution and QoS. We also proposed different signaling schemes to enhance the performance by mitigating any idle periods that may occur when an ONU has little or nothing to send. This enabled the delay reduction to reach more than 80% under normal network conditions, while still keeping a high throughput. The improvement in the delay performance of the proposed schemes is mainly due to the delays independence of ONUs distances from the OLT, and their dependence on their distances from a nearby reflector, leading to more performance gain over centralized schemes as the feeder length is extended.

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