Dynamic Subcarrier Allocation for 100 Gbps, 40 km OFDMA-PONs with SLA and CoS

Wansu Lim, Pandelis Kourtessis, Milos Milosavljevic, John M. Senior

***Abstract*— The quality of service of 100Gbps orthogonal frequency division multiple access passive optical networks (OFDMA-PONs) performing dynamic bandwidth allocation is evaluated. New medium access control protocols and frame formats have been developed, exhibiting hybrid OFDMA/time division multiple access scheduling, for capacity enhancement and granular bandwidth allocation. The sequential dynamic subcarrier allocation algorithms allow the network optical line terminal to grant the optical network units (ONUs) bandwidth using both status and non-status based algorithm. Simulations of a 100 Gbps network with 256 ONUs, 256 subcarriers and 40 km extended-reach demonstrate best network throughputs of 87.5 Gbps and 3 ms packet delays for high priority service classes, even at maximum ONU load. In addition, high service level agreement (SLA) ONUs exhibit 1.56 Gbps maximum capacity and 48.82 kbps granularity.**

***Index Terms*—OFDMA-PON, dynamic bandwidth allocation (DBA), OFDMA, TDMA, class of service (CoS), service level agreement (SLA), quality of service (QoS).**

I. Introduction

With the rise of new content-rich services and the increasing demand for enabling high definition video and cloud computing, the required bandwidth per home is expected to increase steadily to 1 Gbps [1]. Internet corporations, including Google, Amazon and YouTube would considerably benefit from such high capacity with Google already deploying a trial fiber network to cover 50,000 to 500,000 customers with 1 Gbps [2]. To also exploit wireless backhauling, base station (BS) bandwidths for long term evolution advanced (LTE-A) could reach 3 Gbps per site. The solutions proposed to meet such demand should comply with the aggregate rates intended for next generation passive optical network 1 (NGPON1) [3, 4] and NGPON2, while being able to offer a cost-effective PON upgrade path and facilitate the phase-out of legacy technologies.

Research initiatives for NGPONs include the application of advanced multilevel modulation formats and coherent detection [5-7] as well as hybrid wavelength division and time division multiplexing (WDM/TDM) [8, 9]. The transmission of orthogonal frequency division multiplexed (OFDM) signaling formats over PONs can also provide the capacity, reach and cost targets of NGPON2 [10-14]. OFDMA offers high spectral efficiency, due to the orthogonal subcarriers, benefiting also from the availability of efficient software-defined platforms [10, 11] for network implementation. The latter can also provide reduced network cost by reusing established optical networks.

An OFDMA-PON architecture is shown in Fig. 1 [13]. Subcarrier transmission is achieved through a single feeder fiber, spanning from the optical line terminal (OLT) to a remote node (RN). Independently of network segment, optical network units (ONUs) modulate and demodulate their assigned subcarriers, setting those of other ONUs to zero [15-17]. A combiner is commonly used in the RN to multiplex individual OFDM symbols into a common OFDM frame, to be propagated through the feeder fiber to the OLT [13]. The RN could be also implemented by a wavelength selective device, adhering to the network requirements in splitting losses and extended reach [13]. The use, in such scenarios, of power splitters after the first level RN, helps scaling up the aggregate network capacity and ONU count, in a similar manner to WDM/TDM hybrid PONs [17].

Targeting the consolidation of services, it is anticipated that bandwidth in OFDMA-PONs should be largely assigned by dynamic subcarrier allocation (DSCA) protocols able to reshuffle bandwidth among ONUs and improve their quality of service (QoS). Fixed subcarrier allocation (FSCA) could also coexist to provide as an example transparent pipes to base stations (BSs) for wireless backhauling [18]. Incorporating different subcarrier allocation modes in the new OFDMA-PON frames requires additional control fields in their downstream header [19]. Using subcarriers only for bandwidth assignment requires that the number of subcarriers equals or exceeds that of the supported ONUs. Due to high computational complexity imposed on digital signal processors [17], the subcarrier availability in real scenarios can be typically limited. OFDMA/TDMA hybrid protocols are therefore needed to timeshare subcarriers between ONUs, also providing for fine bandwidth granularity.

In addition to the subcarrier number and allocation mode, the network span, RN implementation and US/DS modulation formats are also critical in defining the protocol and dynamic bandwidth allocation (DBA) algorithms of OFDMA-PONs. The modulation adopted specifies cross-layer requirements for the MAC since the signal-to-noise ratio (SNR) of supported subcarriers determines their spectral efficiency and ability to

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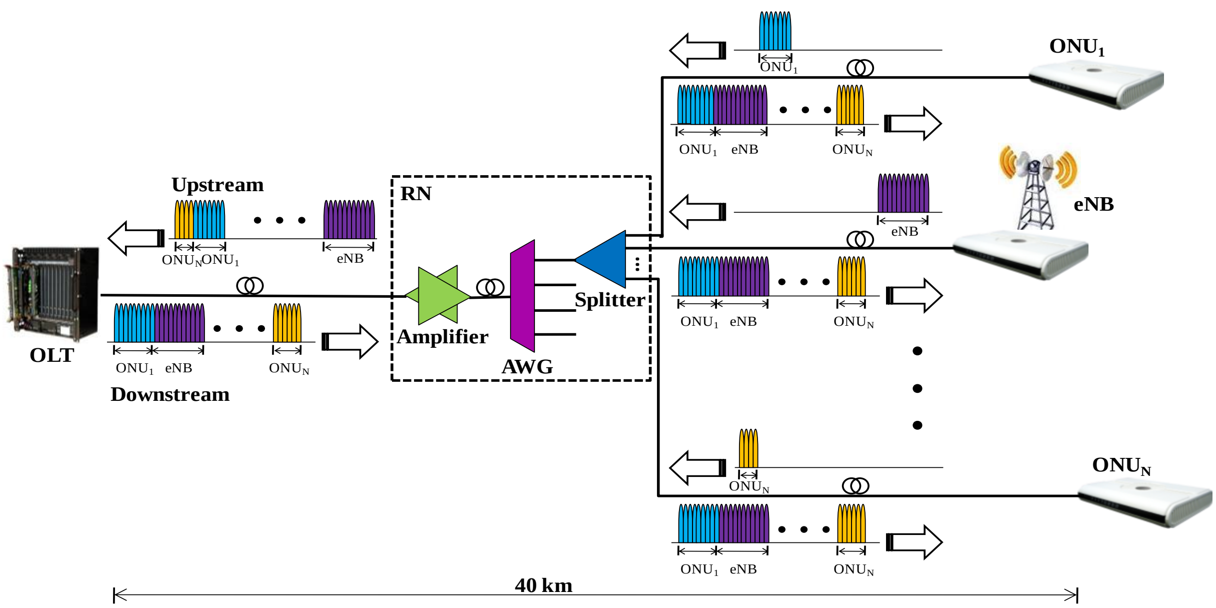

Fig. 1. OFDMA-PON architecture

satisfy the bandwidth requirement of retrospective ONUs [20]. Adaptive subcarrier modulation and cross-layer optimization can therefore highlight further the spectral efficiency of OFDMA [21].

The implementation of hybrid OFDMA/TDMA algorithms for OFDMA-PONs can be summarized by three proposals. The algorithm presented in [22] uses fixed subcarriers for control signaling and hybrid allocation of data, based on conventional Grant/Report polling mechanisms. The frequent communication of report messages every 10.5 µs, allowed by the use of the fixed control subcarriers, achieves accurate representation of ONU queuing information but at an increased computational complexity in the OLT. It also exhibits high occupancy of the upstream bandwidth with report messages. The latter results in moderate network throughput even if the measured packet delay outperforms competitive DBA schemes. Alternatively, [23] proposes two DBA schemes, the dedicated resource allocation (DRA) and shared resource allocation (SRA). DRA only considers the average bandwidth requirement of ONUs, resembling fixed bandwidth allocation. In SRA, subcarriers are initially allocated to individual network slices (segments) to assign a minimum required bandwidth per ONU, and subsequently the remaining bandwidth is time-shared between ONUs using the multi-point control protocol (MPCP) of EPONs. Bandwidth allocation is therefore defined widely by TDMA, resulting in relatively high packet delay. Two DBA protocols are also defined in [24], the fixed burst transmission (FBT) scheme, using a round-robin, interleaved polling with adaptive cycle time (IPACT) algorithm and the dynamic circuit transmission (DCT) scheme, utilizing bandwidth estimation. DCT employs the frequency domain only to allocate bandwidth, using a dynamic short-lived/long-lived circuit with three-way signaling for service connectivity. It could result in increased queuing delays, especially for very short-lived connections, while being limited to rapidly fluctuating traffic.

By contrast the algorithms developed in this paper used both non-status and status based techniques to assess and grant bandwidth to ONUs. The latter allows for direct comparison with protocols above. In particular, scheduling in [23, 24] is based on IPACT which is sensitive to delay and jitter due to the variable polling cycle times [25]. Burst polling [26] is employed to exchange report messages here instead, allowing the support of non-dynamically variable packet delays and the decrease of idle bandwidth since the OLT allocates bandwidth only once all ONU requests are received. In addition, DBA is performed in the presence of three service level agreements (SLAs), critically defining individual ONU groups and their share of the network bandwidth, based on realistic traffic distribution profiles. QoS is further enhanced by including three priority queues to forward incoming traffic from ONU buffers, exhibiting class of service (CoS) differentiation. The performance results attained also compare favorably with those in [22-24]; bearing in mind they are measured for 40km, extended reach links.

II. Non-Status based SDSCA

Bandwidth allocation using a new sequential dynamic subcarrier allocation (SDSCA) algorithm is based on time slots for which subcarriers are assigned by the OLT to the ONUs. An example of the bandwidth map used in this non-status based allocation can be seen in Fig. 2. Each ONU's temporal bandwidth needs are estimated by the OLT during the time of a monitoring window (parallel axis). A monitoring window of 2 ms is used in Fig. 2, split into 16 time slots (t_1...t_{16}), emulating the duration of standard 125 us GPON frames The monitoring window split is also specified in order to provide the required network granularity. This is defined by calculating the number of bits per time slot, corresponding to 48.82 kbits as the result of dividing the data rate of each subcarrier by the time slot duration. During a monitoring window the OLT allocates bandwidth based on the utilization of the time slots, assigned to an ONU in the previous window. In that sense, if an ONU has consumed above 95% of the previous allocated bandwidth, the OLT increases its offered bandwidth by increasing the number of offered time slots [27, 28].

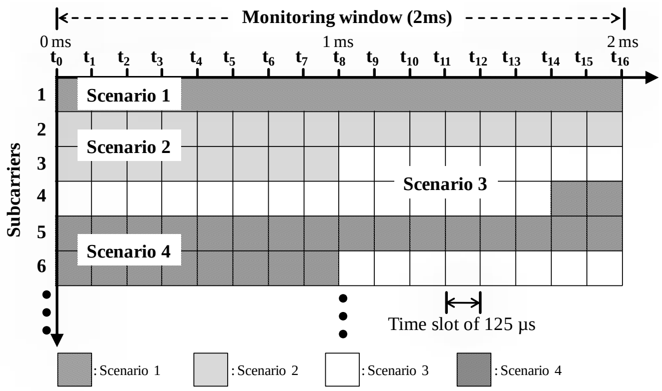

Fig. 2. SDSCA time slot and subcarrier assignment.

The number of additional time slots depends on the overall network bandwidth and specific ONU's SLA. SDSCA considers various scenarios of subcarrier allocation, aiming to increase the network transparency to services and maximize its capacity efficiently by avoiding the formation of idle time slots. These scenarios are shown in Fig. 2. Subsequently the OLT assigns the available subcarriers to accommodate the actual data transfer. The Grant messages communicated to ONUs in that instance distinguish between the four following scenarios.

Scenario 1: ONUs use whole subcarrier(s). For example, each subcarrier is divided into 16 time slots and the total time slots allocated to an ONU is 16.

Scenario 2: The *Requisite Subcarriers* and *Scheduled Subcarriers* are equal and the time slot index is 0 (t_0 at Fig. 2 is the first out of a total 16 time slots). The parameter *Requisite Subcarriers* defines the number of subcarriers necessary to transport ONU data, using the ONU's assigned time slots as a pre-requisite (depends on how many time slots subcarriers are divided into). *Scheduled Subcarriers* represents the number of subcarriers finally assigned by the OLT by means of allowing scheduler to minimize idle time slots. For example, if an ONU is allocated 24 time slots and there are 16 time slots into each subcarrier, the number of *Requisite Subcarriers* is 2.

Scenario 3: *Requisite Subcarriers* is equal to the *Scheduled Subcarriers* and the index of time slot is not 0 ($t_1 – t_{16}$ at Fig. 2).

Scenario 4: *Requisite Subcarriers* is less than the *Scheduled Subcarriers*. Since the allocated time slots are 26, the *Requisite Subcarriers* are 2 but 3 *Scheduled Subcarriers* are assigned to that ONU due to time slot unavailability and scarce distribution.

An example of the data transfer achieved by each ONU for the different bandwidth allocation scenarios is illustrated in Fig. 3. The total upstream capacity is 100 Gbps, the number of subcarriers 256, the number of ONUs 256 and the data rate per subcarrier 390.62 Mbps (100 Gbps / 256 subcarriers). During a monitoring window time of 2ms, ONUs in *Scenario 1* transmit 390.62 Mbps. This has been calculated by accounting for the number of subcarriers assigned to an ONU over a specific period of the monitoring window. This is illustrated in Fig. 3 for *Scenario 1* where ONUs use one subcarrier for the whole duration of the monitoring window. In *Scenario 2*, ONUs transmit at two different data rates, 781.24 Mbps using two subcarriers until 1 ms and 390.62 Mbps using one subcarrier until 2 ms. In *Scenario 3*, ONUs use three different data rates, 390.62 Mbps with one subcarrier until 1 ms, 781.24 Mbps with two subcarriers until 1.75 ms and 390.62 Mbps with one subcarrier until t_{16}. In *Scenario* 4, ONUs also use three different data rates, 781.24 Mbps until 1 ms, 390.62 Mbps until 1.75 ms and 781.24 Mbps until 2 ms.

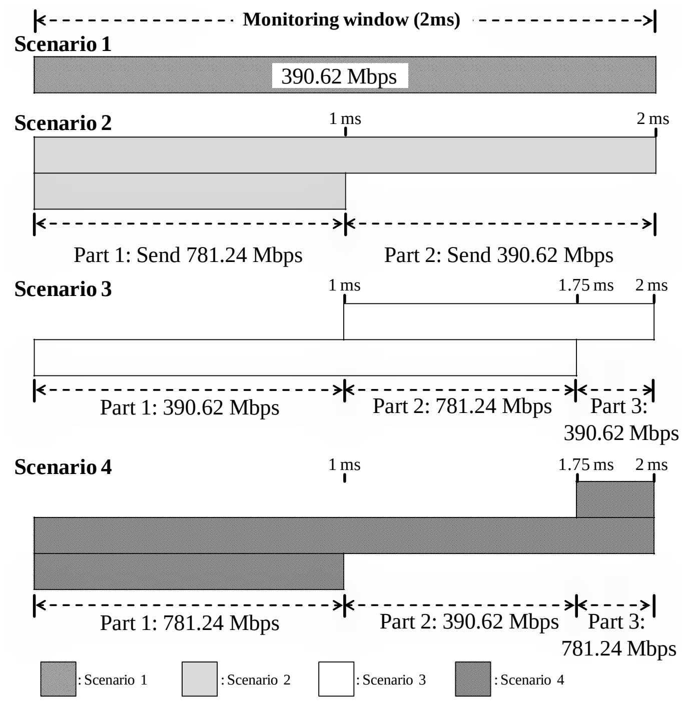

Fig. 3. The SDSCA four scenarios and their corresponding ONU propagation rates.

III. Status based SDSCA

The status based SDSCA algorithm employs a bandwidth assignment methodology using the exchange of report messages. In this case the algorithm incorporates three queue priorities to simulate three classes of traffic. The OLT calculates the grants for each ONU, and then transmits the grants in a gate message at the fixed cycle time. On reception, ONUs release traffic upstream using the allocated subcarriers, based on the receiving grant size and specified start time, suggesting that every ONU is polled periodically. Since all gate messages should be sent to each ONU at the specified time in a burst fashion, the next polling time for each ONU can be predicted, benefiting delay-sensitive services and therefore enhancing QoS. In addition, the algorithm does not consume downstream bandwidth by frequently polling the ONUs at low payloads.

To proceed with the analysis of the bandwidth allocation process, the number of ONUs is given by N, the upstream data rate consists of R bps and the grant cycle time is given by T_{cycle}. The latter represents the time interval during which all active ONUs can transmit payload data and/or report messages to the OLT. Each ONU incorporates three SLA levels, being the standard in practical network deployments, and manages, as already stated, three queues to support QoS according to different classes of traffic. Guard intervals, T_g, are necessary to avoid collisions from timing fluctuations between ONUs.

The *total* available bandwidth, B_{total}, is calculated by $B_{total} = (T_{cycle} - N \times T_g) \times R$. A *basic* bandwidth is allocated by the algorithm to each ONU, weighted by each ONU's SLA. In addition, the *guaranteed* bandwidth of each ONU is defined as, B_s^{grt} , $s \in \{\text{index of SLA} | 1, 2, 3\}$ and consists of the *basic* bandwidth, B_s^{basic}, and the extra bandwidth, B_s^{ext}, that could be required by ONUs at arbitrary polling cycles. Incorporating the different weights, W_s, for each ONU, the *basic* and *extra* bandwidths in the algorithm are respectively defined by:

$$B_s^{basic} = \left[\frac{B_{total}}{N} \right] \times W_s \quad (1)$$

$$B_s^{ext} = (B_{total} - \sum_{s=1}^{3} B_s^{basic} N_s) \times \frac{W_s}{\sum_{s=1}^{3} W_s N_s} \quad (2)$$

Let B_{total}^{req} be the sum of the requested bandwidth for all ONUs, calculated as:

$$B_{total}^{req} = \sum_{i=1}^{N} B_i^{req} \quad (3)$$

Each bandwidth requirement of each ONU includes information for all three of its queues as given by:

$$B_i^{req} = \sum_{j=1}^{3} B_{i,j}^{req} \quad (4)$$

Note that j is the index of traffic classes. Thus, the assigned bandwidth for each i-th ONU, B_i^{assign}, is determined as follows:

$$B_i^{assign} = \begin{cases} B_i^{req} & , B_{total}^{req} < B_{total} \\ B_s^{grt} & , B_{total}^{req} > B_{total} \end{cases} \quad (5)$$

At this point, some ONUs might have less traffic, $B_s^{grt} > B_i^{req}$, while others might require more than the guaranteed bandwidth, $B_s^{grt} < B_i^{req}$. When $B_s^{grt} > B_i^{req}$, this results in a total surplus bandwidth, $B_{total}^{surplus} = \sum_i^M (B_s^{grt} - B_i^{req})$ where M is the set of low-loaded ONUs. When $B_s^{grt} < B_i^{req}$, a surplus bandwidth, $B_i^{surplus}$, is allocated to the i-th ONU as follows:

$$B_i^{surplus} = \frac{B_{total}^{surplus} \times (B_i^{req} - B_s^{grt})}{\sum_{k \in K} (B_k^{req} - B_s^{grt})} \quad (6)$$

In eq. (6) K defines the set of heavily loaded ONUs. The algorithm distributes evenly the surplus bandwidth among these heavily loaded ONUs using:

$$B_i^{assign} = \begin{cases} B_i^{req} & , B_i^{req} < B_s^{grt} \\ B_i^{req} + B_i^{surplus} & , B_i^{req} > B_s^{grt} \end{cases} \quad (7)$$

IV. Protocol Performance Evaluation

To evaluate the proposed algorithms in terms of the network throughput, end-to-end packet delay and packet loss rate, OPNET models were developed, exhibiting an OFDMA-PON with 100 Gbps upstream capacity, composed of 256 ONUs with 256 subcarriers of 390.62 Mbps each. The distance between the OLT and each ONU is extended to 40 km to evaluate the new protocol performance and algorithm designs at distances compatible with NGPON2. Three SLAs, SLA_t, t=0, 1, 2, exhibiting high to low superiority have been considered. The number of ONUs in each service level is set to 16, 80 and 160. The guaranteed bandwidth for SLA_0 ONUs is 725 Mbps for SLA_1 ONUs 550 Mbps and for SLA_2 ONUs 200 Mbps. The figures above correspond to a guaranteed network bandwidth of 87.6 Gbps. The algorithms are arranged so that the remaining 12.4 Gbps bandwidth is primarily allocated to the high SLA ONUs.

Network traffic is implemented by a self-similar model with a typical Hurst parameter of 0.8 to simulate practical network patterns. The packet size is uniformly generated between 64-1518 Bytes. The buffer size of each ONU is limited to 10 Mbytes with grant processing and propagation delays set to 5μs and 5μs/km respectively. For the status based algorithm, a guard time of 0.5 μs is used between ONUs. CoS differentiation has also been accounted for with CoS_0 to CoS_2, representing high to low priority queues. To simulate a realistic OFDMA-PON, 20% of the generated packets are assigned to CoS_0 and the rest 80% are divided between CoS_1 and CoS_2.

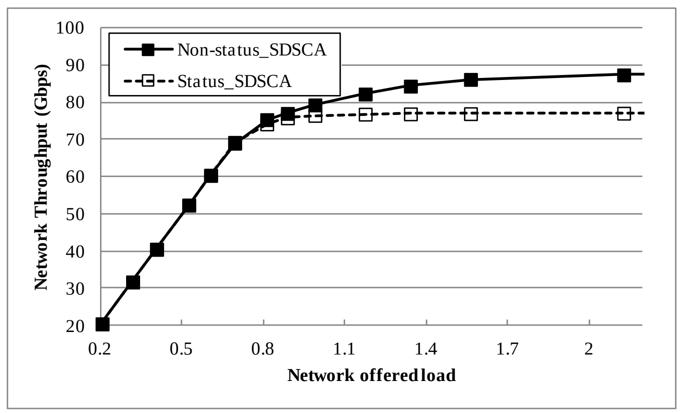

Fig.4. Network throughput results with status and non-status based scheduling.

The characteristics for network throughput against offered load in Fig. 4 confirms that non-status based SDSCA achieves increased throughput. The obtained figure of 87.5 Gbps, exhibits an improvement in channel utilization rate by 13.5%, compared to the status based SDSCA that stalls at around 77 Gbps. The saturated throughputs mainly depend on the idle period formed in the 2 ms monitoring window due to the propagation delay of the report and grant message exchanges between ONUs and the OLT for the allocation of bandwidth. This applies particularly for the status based scheme since ONUs cannot transmit any data before they have received their grant messages from the OLT. Due to the 40 km distance between ONUs and the OLT, the propagation delay of the grant and report messages is 200 us (i.e. 40 km × 5 us/km). Therefore the total idle period is 400 us which is 20% of the 2 ms monitoring window. Directly associated with this 20% drop, is the maximum measured throughput of 77 Gbps out of the total upstream network capacity of 100 Gbps. Similarly the non-status based protocol achieves an increased 87.5 Gbps throughput since it benefits from not including the transmission of report messages and subsequently the associated idle period is reduced to 200 us.

To explore the data transfer quality, Fig. 5 exhibits the end-to-end packet delay for all three SLAs versus ONU offered load. The ONU offered load represents the amount of traffic generated for each ONU emulating thus different practical requirements per user. The average traffic load is 390.62 Mbps, represented in Fig. 5 by 1.0. This value is obtained by dividing the network capacity by the total number of ONUs. However, it is important to mention that this traffic load does not correspond to an actual data rate a specific ONU can use for upstream transmission. Upstream transmission rates are defined by the OLT by means of the applied scheduling algorithm. Depending particularly on SLA the minimum transmission rate for an ONU can be as low as 48.82 kbps, assuming that a single time slot is utilized per second as explained in section II, and up to 1.56 Gbps for an ONU utilizing all available time slots of their allocated subcarriers. The peak rate of 1.56 Gbps is the result of multiplying 390.62 Mbps by 4 being the maximum number of subcarriers allocated by the OLT to SLA_0 ONUs. It can be observed that the threshold ONU loads to achieve low transmission delay with the status based and non-status based SDSCA, correspond to 0.7 and 0.6, respectively. These figures confirm that in the worst case scenario, OFDMA-PONs with SDSCA can provide low delay transmission when the overall network offered load is not in excess of 70 and 60 Gbps, respectively ([0.7 or 0.6] × 390.62 Mbps × 256 ONUs) for a 100 Gbps network. The 10 Gbps increment represents a 16.6% improvement in comparison with the non-status based algorithm.

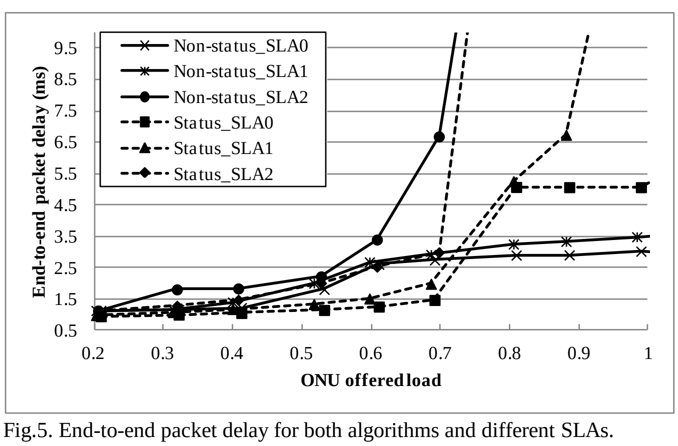

Fig.5. End-to-end packet delay for both algorithms and different SLAs.

To elaborate further, SLA_2 ONUs exhibit increased delay figures, forming early on the ONU offered load scale, for both the status and non-status algorithms. This results from the fact that SLA_2 ONUs are allocated less bandwidth compared to both SLA_0 and SLA_1 and due to the lower priority with which they are allowed to transmit data they exhibit higher delay. To compare directly between the two algorithms, in the ONU offered load range between 55% and 70%, Fig 5 confirms that non-status scheduling lags in performance with respect to its status counterpart. As explained in section II the non-status policy is to directly increase next cycle's allocated bandwidth if the OLT has indications that ONUs at the previous cycle have extensively used their allocated resources. This process is performed at strict SLA order prioritizing the high and middle SLAs. Therefore even at low traffic loads, monitoring could result in over servicing the higher SLA ONUs, restricting the bandwidth available for use by SLA_2 ONUs. In contrast, the use of the reporting mechanism in the status based algorithm allows a more accurate distribution of bandwidth that at lower traffic load in particular SLA_2 ONUs can be still supported with their intended bandwidth. In overall, before the measured packet delay has reached the 3 ms marker for time-sensitive traffic, the status-based algorithm allows SLA_2 ONUs to extend their acquired bandwidth from 226 Mbps, achieved with non-status scheduling, to 273 Mbps. Considering low SLA ONUs acquire primarily moderate rate services, the additional 47 Mbps bandwidth could be used to support supplementary multimedia services including education-on-demand, online gaming and video conferencing. Over and above 70% of the ONU offered load, the results record superior performance of non-status over the status algorithm. Non-status scheduling demonstrates almost half the delay at 80% and 90% ONU loads for SLA_0 and SLA_1, respectively. This performance trend occurs because for increased transfer load, ONU queues get fuller, in strict SLA order, and hence the non-status based allocation process becomes naturally more accurate. Also in the absence of the need to communicate report messages and the effect this has on reducing propagation delays, non-status based scheduling enhances its efficiency with increasing load.

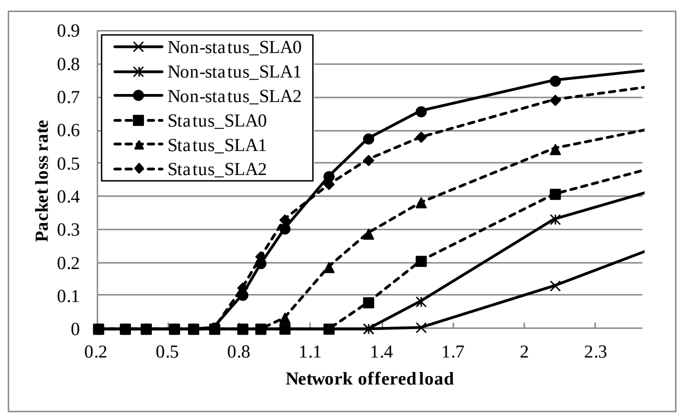

Fig.6. Individual ONU group packet loss rate per SLA

Furthermore, Fig. 6 provides a comparison of the packet loss rate distribution of the two algorithms. Fig. 4 has confirmed that non-status scheduling can achieve higher overall throughput that is directly related to the recorded packet loss rate. Following the analysis of Fig. 4 SLA_2 ONUs are expected to exhibit in both cases almost identical loss rate performance. This is confirmed by Fig. 6 where a loss-free transmission is sustained for both algorithms up to about 70 Gbps (0.7 × 100 Gbps). Comparing the SLA_0 and SLA_1 ONU responses, the threshold of loss-free transmission is extended from 117 Gbps and 90 Gbps ([1.17 or 0.9] × 100 Gbps) using the status algorithm to 156 Gbps and 134 Gbps ([1.56 or 1.34] × 100 Gbps) using non-status. The fact that some of the data rates above exceed the network capacity can be justified considering that the traffic generator should overflow the individual ONU queues before ONUs start experience buffering and potentially packet loss. The point at which ONUs overflow represents their maximum stored data rates and depends on their guaranteed bandwidth and therefore SLA.

When ONUs receive their upstream bandwidth maps from the OLT, both SDSCA algorithms also allow for intra-ONU scheduling, by means of a strict priority queue method. As already defined the simulator exhibits three traffic types distinguished by CoS_0, CoS_1 and CoS_2 to represent high, medium and low queue priorities respectively and as a result the sequence of data transfer. While all CoSs should demonstrate low packet delay for moderate ONU and network offered load, depending on each SLA's available transmission bandwidth ONU buffering commences when the generated traffic approaches or exceeds the maximum network capacity. To that extent longer packet delay and packet loss rate are expected for CoS_2 at high network load, allowing for bandwidth to be effectively allocated to higher priority traffic classes. Similarly, CoS_1 traffic will start experiencing longer packet delay and packet loss rate with further increases in load.

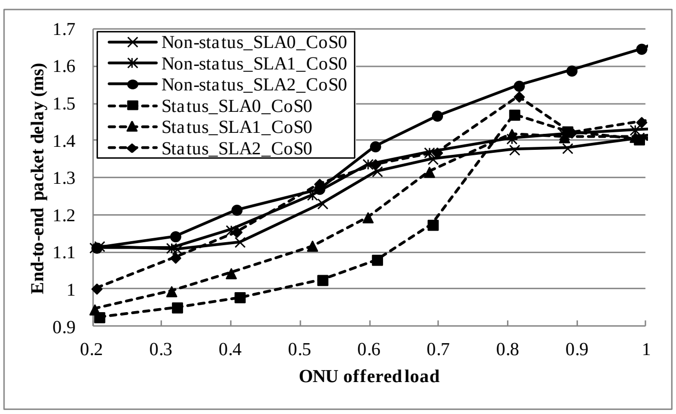

Fig.7. End-to-end packet delay for CoS_0 ONUs.

Fig. 7 displays the recorded packet delay of CoS_0 ONUs versus ONU offered load at all three SLAs. Since CoS_0 traffic has the absolute priority, the measured delay figures are consistently less than 2 ms, even at an ONU traffic load of 1.0, regardless of SLA level and the implemented algorithm. Similar characteristics were also observed for CoS_1 and therefore are not included in the paper.

By contrast to CoS_0 and CoS_1 traffic, the time insensitive class, CoS_2, has the lowest priority in accessing the network and, as a result, is expected to present the worst performance in packet delay. This is confirmed in Fig. 8, which displays significantly increased delay figures among the three service levels. For SLA_0 and SLA_1 the delay using the non-status based algorithm is significantly less than that observed with the status based algorithm at high traffic loads. Fig. 8 displays a reduction in delay by more than a factor of two for SLA_0 ONUs at 80% of ONU offered load. Correspondingly, an eight-fold reduction in delay is also presented for SLA_1 ONUs at around 100% of ONU load. The significance of the reduced delay values for each SLA ONU in actual network deployment scenarios is crucial since it represents a corresponding reduction in ONU buffer packet waiting times. This property allows the feeder section in the PON to accommodate increased volume of burst streams, depending on network penetration and service level distribution among ONUs.

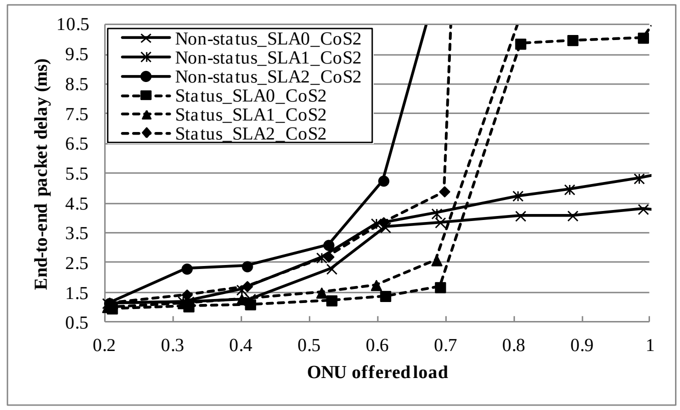

Fig.8. End-to-end packet delay for CoS_2. ONUs

Finally, in addition to mean packet delay, the network packet loss rate versus network load is also presented since it is a critical performance measure to guarantee QoS for all CoS traffic. Since time-sensitive traffic, CoS_0, can always be communicated with low packet delay, no packet loss is expected for 40 km OFDMA-PONs in the presence of the non-status based algorithm.

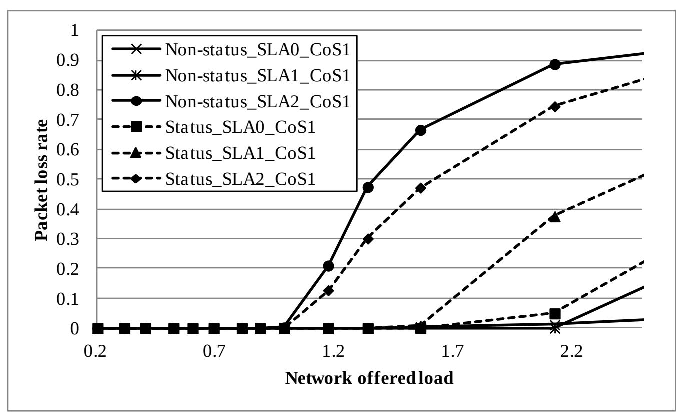

Fig. 9. Packet loss rate for CoS_1 ONUs.

Hence CoS_1 and CoS_2 traffic characteristics are provided in Fig. 9 and 10, respectively. For CoS_1 traffic, considering the SLA_1 ONUs, the loss-free transmission is extended from 134 Gbps (100 Gbps×1.34) with the status based algorithm to 156 Gbps (100 Gbps×1.56) with non-status, hence providing an extra 22 Gbps network throughput.

Similarly, the loss-free transmission for the time-insensitive traffic, CoS_2, is still extended from 98 and 88 Gbps to 117 and

98 Gbps providing an extra 19 and 10 Gbps network throughput for SLA_0 and SLA_1, respectively.

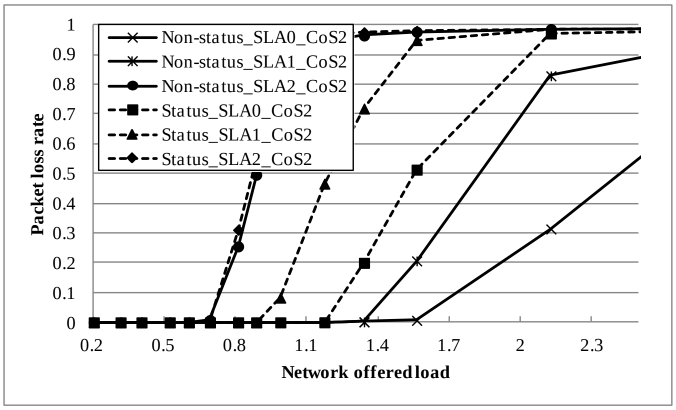

Fig. 10. Packet loss rate for CoS_2 ONUs.

V. Conclusions

The bandwidth assignment and performance evaluation of new algorithms has been described exhibiting SLA and CoS differentiation for 40km extended-reach, 256-split OFDMA-PONs with 256 subcarriers and 100 Gbps aggregate rates. By integrating the advantages of TDMA and OFDMA, the new OFDMA/TDMA algorithms provide high SLA ONUs with 1.56 Gbps capacity, while exhibiting the required service granularity by enabling data rates down to 48.82 kbps. The network subcarriers are time shared using 16 time slots providing standard 125 μs GPON frames that if allocated to a single ONU, up to 390.62 Mbps can be supported per subcarrier. Subcarriers are assigned to ONUs in strict SLA order, exhibiting realistic ONU traffic distribution profiles. Three priority classes are also incorporated to simulate different traffic types.

Two approaches of establishing connectivity between the ONUs and OLT have been demonstrated. A non-status based scheme allows rapid bandwidth allocation based on the monitoring of ONU bandwidth transfers and a fine status based algorithm accounting for actual ONU requests. Burst polling is used in association with the latter, allowing the support of non-dynamically variable packet delays and the enhancement of network utilization efficiency by reducing idle bandwidths. This is because the OLT allocates bandwidth only after all bandwidth requests have been received by the ONUs.

Performance evaluation figures confirm that for lower traffic load (below 70%) there is an overall 1 ms difference in delay in favor of ONUs using the status based scheduler. For higher traffic loads, however, (above 70%) the performance, except for the low SLA ONUs, has reversed and the delay of the non-status based protocol is at least 2 ms lower. This performance trend can be justified if it is considered that for increasing transfer rates, ONU queues accumulate traffic, and the non-status based allocation process becomes simplified as well as naturally becoming more accurate, since the probability of higher SLA ONUs, in particular, operating successively at full resources is increased. In addition, the absence in non-status based algorithm of the need to communicate report messages imposes less propagation delays, contributing to the lower performance at high traffic load.

To explain the performance at traffic loads between 50% and 70%, the delay difference of SLA_2 ONUs between non-status and status is maximized in favor of the latter because the generated traffic in this period catches up and eventually surpasses their guaranteed bandwidth. With respect to the network throughput, the non-status based protocol has obtained approximately 10 Gbps more throughput (87.5 Gbps versus 77 Gbps) demonstrating the enhanced throughput of OFDMA at increased network traffic load. The 77 Gbps of the status based algorithm corresponds to an 80% utilization of the 2 ms polling cycle, due to the 0.4 ms propagation delay incurred by report message exchanges, when considering the 100 Gbps total upstream capacity and 40 km extended network reach.

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