“Definition and evaluation of algorithms for dynamic bandwidth allocation in ACCORDANCE”

D4.3

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Abstract:
The ACCORDANCE project is expected to propose and evaluate novel MAC protocols and algorithms which will perform dynamic bandwidth allocation of subcarriers and time slots, preferably with minimal modifications to existing standard frame formats.
Task 4.3 is intended to develop algorithms suitable for the MAC protocols defined in T4.2. Those algorithms will be able to distribute the ACCORDANCE bandwidth (both downstream and upstream) in an efficient way, respecting the individual service level agreements (SLAs) of users and providing optimal QoS/QoE levels, especially for very demanding types of traffic (e.g. real-time applications).
D4.3 reports on a series of developed algorithms for OFDMA-PONs that distinguish between EPON and GPON-based scheduling, allocation in the subcarrier domain only (DSCA algorithm) or jointly in subcarrier and time promoting hybrid OFDMA/TDMA schemes (SDSCA and RDSCA algorithms) and finally on the mechanism used by the OLT to allocate bandwidth to ONUs (monitoring or reporting). All algorithm designs have been evaluated using the event-driven packet-based simulator OPNET. Individual performances are compared and contrasted in order to establish their availability for ACCORDANCE. Network spans from 20 km up to 100 km have been considered to confirm protocol suitability for migration scenarios.

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References

[1] "MAC layer requirements for the ACCORDANCE Network - Update", Deliverable D4.4, ACCORDANCE, FP7 – ICT– GA 248654, June 2011

[2] "Definition of MAC protocols supporting FDM/OFDM operation", Deliverable D4.2, ACCORDANCE, FP7 – ICT– GA 248654, February 2011

[3] "Final report on network architecture and elements' requirements", Deliverable D2.2, ACCORDANCE, FP7 – ICT– GA 248654, April 2011

[4] "Network architecture and elements", Deliverable D2.1, ACCORDANCE, FP7 – ICT– GA 248654, August 2010

[5] K. Kanonakis, I. Tomkos, T. Pfeiffer, J. Prat, P. Kourtessis, "ACCORDANCE: A novel OFDMA-PON paradigm for ultra-high capacity converged wireline-wireless access networks," in Proc. ICTON 2010, pp. Tu.A1.2.

[6] F. Effenberger, H. Mukai, P. Soojin, and T. Pfeiffer, "Next-generation PON-part II: candidate systems for next-generation PON," *IEEE Comm. Mag.*, vol. 47, pp. 50-57, Nov. 2009

[7] A. Ghosh et al., "LTE-advanced: next-generation wireless broadband technology," *IEEE Wireless Commun.*, vol. 17, pp. 10-22, June 2010.

[8] ITU-T, "G.987.3 10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) specifications" ITU-T 2010.

[9] IEEE Std 802.3av-2009, Carrier Sense Multiple Access With Collision Detection (CSMA/CD) Access Method and Physical Layer Specification, Amendment 1: Physical Layer Specifications and Management Parameters for 10 Gb/s Passive Optical Networks, 2009.

[10] "MAC layer requirements for the ACCORDANCE Network", Deliverable D4.1, ACCORDANCE, FP7 – ICT– GA 248654, August 2010

[11] K. Kanonakis and I. Tomkos, "Improving the efficiency of online upstream scheduling and wavelength assignment in hybrid WDM/TDMA EPON networks," IEEE J. Sel. Areas Commun., vol. 28, no. 6, pp. 838–848, Aug. 2010.

[12] W. Lim, A. Gliwan, P. Kourtessis, K. Kanonakis, I. Tomkos and J. M. Senior, "MAC Protocol Design for the Support of DBA in OFDMA-PON Networks," in Proc. Future Network and Mobile Summit 2011, paper. 4B15, Warsaw 2011

[13] W. Lim, Pandelis Kourtessis, Milos Milosavljevic, John M. Senior, "Dynamic Subcarrier Allocation for OFDMA-PONs with Monitoring Mechanism", ", in Access Networks and In-house Communications, OSA Technical Digest (CD) (Optical Society of America, 2011), paper AMC3, Toronto 2011

[14] W. Lim, C. Yun, Y-M. Yang, H. Lee, and K. Kim, "Burst-Polling-Based Dynamic Bandwidth Allocation Using Adaptive Minimum Guaranteed Bandwidth for EPONs," *IEEE/OSA J. Opt. Commun. Netw.,* vol. 1, pp. 594-599, 2009.

[15] K. Kanonakis and I. Tomkos, "Detaining online upstream scheduling in WDM/TDMA EPONs," in 36th European Conference and Exhibition on Optical Communication, ECOC 2010, Torino, Italy, Sep. 2010.

[16] J. Tang and K. Shore, "30-Gb/s signal transmission over 40-km directly modulated DFB-laser-based single-mode-fiber links without optical amplification and dispersion compensation," J. Lightw. Technol., vol. 24, no. 6, pp. 2318–2327, Jun. 2006.

[17] J. Tang, P. Lane, and K. Shore, "High speed transmission of adaptively modulated optical OFDM signals over multimode fibres using directly modulated DFBs," J. Lightw. Technol., vol. 24, no. 1, pp. 429–441, Jan. 2006.

[18] E. Giacoumidis, J. Wei, X. Jin, and J. Tang, "Improved transmission performance of adaptively modulated optical OFDM signals over directly modulated DFB laser-based IMDD links using adaptive cyclic prefix," Opt. Express, vol. 16, no. 13, pp. 9480–9494, Jun. 2008.

[19] E. Giacoumidis et al., "Adaptive-modulation-enabled WDM impairment reduction in multichannel optical OFDM transmission systems for next generation PONs," IEEE Photonics Journal, vol. 2, no. 2, pp. 130–140, Mar. 2010.

1. Executive Summary

The scope of deliverable 4.3 (D4.3) is to study the algorithms developed for the implementation of new Medium Access Control (MAC) designs for Orthogonal Frequency Division Multiple Access Passive Optical Networks (OFDMA-PONs) and perform network evaluations, with ACCORDANCE being the underlying infrastructure. To the benefit of the reader, a brief summary from D4.4 [1] of the parameters exhibiting significant impact on the network MAC is included in this deliverable's opening chapter. The network terminations, deployment scenarios, application targets and services have subsequently provided the tools in D4.2 [2] for the extension of the 10 Gbit/s Ethernet PON (10GEPON) and 10 Gigabit PON (XGPON) frames and control fields to allow OFDMA operation. Key protocol features are highlighted in chapter 2, providing the criteria based upon the development of algorithms has been conducted. Following the standardisation incentives of IEEE and ITU-T for Next-Generation PONs, the ACCORDANCE algorithms account for both Ethernet PON (EPON)-based and Gigabit PON (GPON)-based networks. Both the protocol and algorithm deliverables will benefit from updates, aiming to deliver the finest MAC designs for OFDMA-PONs, while specifying the option best suiting the ACCORDANCE Optical Line Terminal (OLT) and Optical Network Unit (ONU) Field Programmable Gate Array (FPGA) transceivers to be used during project demonstration.

Chapter 3 extends into the description of Dynamic Subcarrier Allocation (DSCA) algorithms enabling high-capacity transfer using only the subcarrier domain. Network evaluations have been performed with reference to both Service Level Agreement (SLA) and Class of Service (CoS) differentiation based on GPON scheduling. Chapter 4 introduces OFDMA/ Time Division Multiple Access (TDMA) hybrids to exhibit increased granularity in bandwidth allocation. The GPON-based, sequential-DSCA (SDSCA) algorithm is evaluated in the first instant. Two methodologies are considered to assign subcarriers/time-slots to ONUs (monitoring and reporting). To explore the MAC granularity further, chapter 5 studies the dynamic arbitration of subcarriers in an EPON-based MAC framework based on online-scheduling and the reporting of ONU bandwidth requests. Rectangulars are formed to designate the assignment of time slots to subcarriers, introducing the rectangular-DSCA (RDSCA) algorithm. RDSCA is extended in chapter 6 to include adaptive subcarrier modulation (ASM). Increased aggregate network capacity is achieved while improving Quality of Service (QoS) with acceptable physical layer performance degradation for link lengths ranging from 20 to 100 km. Finally chapter 7 describes the merits of the monitoring SDSCA algorithm, targeting the 100 km migration scenario. In all cases complete process models have been developed in OPNET, adapting to all possible scenarios and network specifications.

2. Summary of the MAC Defining Elements

2.1. ACCORDANCE ARCHITECTURE

The ACCORDANCE architecture, shown in Figure 1, exploits the merits of OFDMA in scaling up the access network in reach and aggregate rates while achieving convergence of technologies. The details of its functionality and features have been extensivelly covered in preceeding deliverables [3], [4]. It would be beneficial nevertheless to briefly summarise the parameters that have an impact on the designed OFDMA MAC and particularly on the projected algortihms. These consist of Physical Layer (PHY) parameters as well as network features. The former comprise the network reach, remote node (RN) implementation type, the number of subcarriers and ONUs, the upstream/downstream bitrates and the upstream/downstream modulation schemes. The latter relate to the bandwidth allocation criteria used and how SLA and CoS differentiation can be achieved in the bandwidth allocation algorithms.

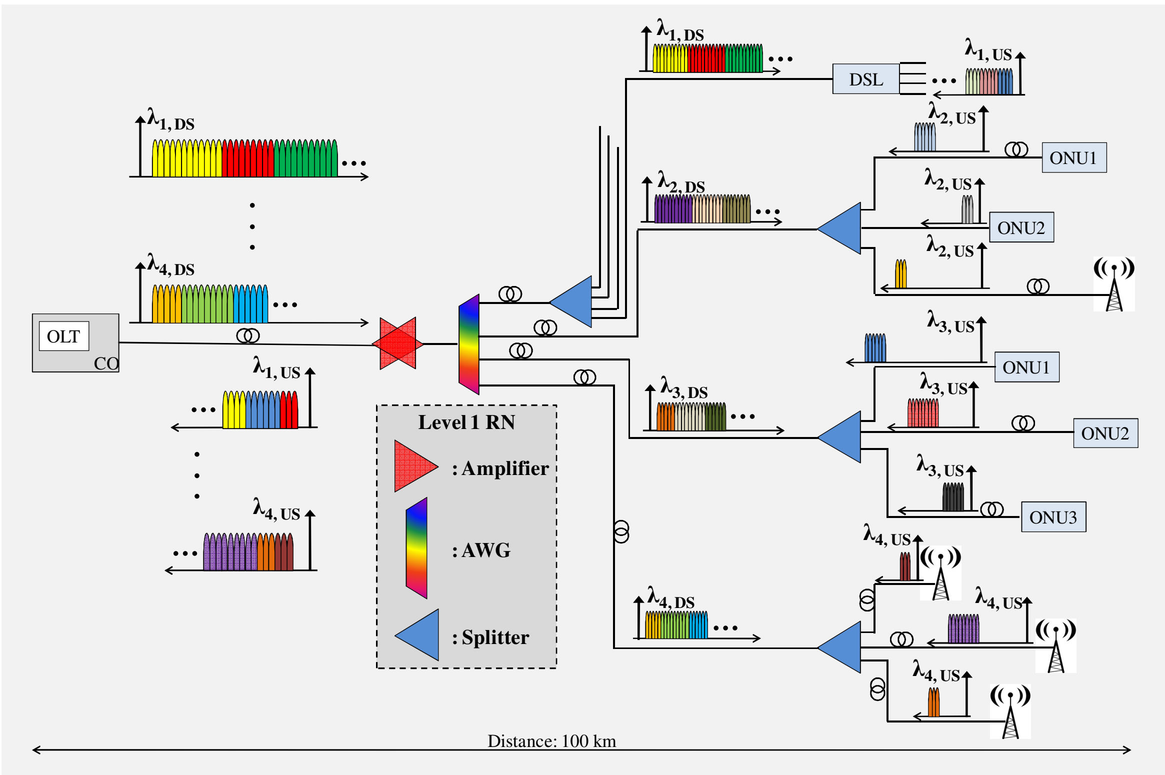

Figure 1: The ACCORDANCE Network.

For the purposes of this delivearble, we consider a simplified ACCORDANCE topology, comprising the OLT located at the Central Office (CO) of the Service

Provider (SP) and multiple ONUs at the user premises. A single fibre link connects the OLT to an intermediate RN, consisting of a passive optical coupler/splitter. The optical spectrum in ACCORDANCE is organized in groups of subcarriers called segments, possibly belonging to different service providers and addressing different parts of the network [5].

In ACCORDANCE the ONUs terminated to the network OLT represent different technologies, e.g. OFDMA, legacy E/GPONs, their updates and wireless/mobile ONUs. They can provide service to residential users, corporations and small/medium enterprises as well as Telco services by utilizing Fiber-to-the-Home (FTTH) or Fiber-to-the-Building/Curb (FTTB/FTTC) aggregation nodes. The impact of this distinction serves establishing the requirements in upstream/downstream user rates per wavelength as well as the unique requirements in QoS, affecting the bandwidth allocating methodology.

The ACCORDANCE MAC has foreseen the development of new Ethernet frame formats, originated from legacy PON frame structures, that could be extended in some cases to accommodate wireless backhauling. Legacy TDMA allocation is not examined since legacy PONs will only be transparently transmitted over ACCORDANCE. TDMA allocation of bandwidth is only investigated in connotation with OFDMA to improve the network granularity by parting the OFDMA spectrum subcarriers in time slots using intra-segment bandwidth allocation algorithms. The additional property of network segments to be able in some cases to benefit by the dynamic assignment of part of the OFDMA spectrum has also been singled out leading to inter-segment bandwidth allocation. This involves partitioning the downstream OFDMA spectrum in segments of varying widths and spectral location to accomodate different bandwidth applications. In this deliverable only intra-segment bandwidth allocation will be examined. Inter-segment operation will be accounted for at the current deliverable’s update due in the final year of the project.

Examples of aggregate rates for Next Generation-PON1 (NG-PON1) [6], range from up to 400 Mbps guaranteed bit rates for residential users and small businesses, considering emerging applications such as Ultra High Definition Television (UHDTV), 3-Dimensional TV (3DTV), real-time TV/Video on Demand (VoD) zapping and streaming, to several tens of Gbps for corporations and Telco services, also requiring enhanced latency efficiency. In addition, E-UTRAN NodeB (eNB) bandwidths could reach up to 3 Gbits/s per site at future Long Term Evolution (LTE) deployments [7], while the overall performance of the OFDMA MAC for successful wireless backhauling in terms of packet delay should also conform to the requirements of LTE. D4.4 [1] has already identified the requirements of the ACCORDANCE MAC design in such scenario. Protocol and algorithm implementation will be the subject of the updates of D4.2 [2] and of the current deliverable.

The network reach is naturally significant when developing algorithms and expecially when moving towards longer-reach implementations. To that extent, the performance figures must still be achieved given the larger propagation delays (and perhaps increased differential delays among ONUs). In line with the deployment scenarios defined within ACCORDANCE [3], [4], networks ranging from typical 20 km OLT-ONU spans, up to long-reach 100 km distances will be considered. The correlation between the number of ONUs and subcarriers largely affects bandwidth allocation. It becomes obvious that bandwidth assignment only in the subcarrier domain is not possible if the number of available subcarriers is less than the number of ONUs (or, even further, than the total number of different SLAs – more than one SLA can be supported per ONU). Therefore highly granular, hybrid OFDMA/TDMA solutions are employed to share a single or multiple subcarriers between different ONUs in time [1]. If a sufficiently large amount of subcarriers can be dynamically assigned to each ONU though, the OLT only uses the frequency domain, supported by capacity control, avoiding complex TDMA algorithms.

Finally, the RN in the ACCORDANCE infrastructure and in any OFDMA-PON is widely implemented by a power coupler/splitter but a wavelength selective device could also be used. In view of the presence of an Array Waveguide Grating (AWG) at Level 1 RN, different wavelengths are routed to different parts of the network and the algortihms will have to incorporate a third level of multiplexing to assign OFDMA/TDMA subcarrier/slots to more than one (1:4, 1:8) supported wavelengths. The AWG scenario has not been investigated in the current document with respect to developoing algorithms and remains to be seen if it will be part of the deliverable update. The amplifier, also shown in Figure 1, does not impose a requirement on the OFDMA MAC since its potential use will be simulated by the network reach corresponding to the respective deployment scenarios.

2.2. ACCORDANCE Frame Functionalities and Control Fields

Since the new MAC design should provide an evolutionary extension of existing protocols, this section summarises the modifications imposed in D4.2 [2] on the XGPON, G.987.3 [8] and 10GEPON, 802.3av-2009 [9] standards, with respect to frame functionalities and control fields, to accommodate the requirements for downstream and upstream transmission of OFDMA-PONs. Since ACCORDANCE targets Next Generation PON (NGPON), it is the aim of this deliverable to present new algorithm designs exploiting both GPON and EPON scheduling. The update of D4.3 at the end of the project could be used to process those algorithms and to assess the best suited for OFDMA-PONs. The fields summarised below have helped define the conditions of the ACCORDANCE algorithm flowcharts and as a result provide a useful introduction to the developed algorithms.

The ACCORDANCE Upstream (US) frame integrates fields such as the ONU_ID and CoS, the ONU_LSc_ID and ONU_HSc_ID, defining the start and end of subcarrier ranges, the service provider identifier, SP_ID, field allowing for multiple providers' support and the ONU_Type field to identify the various ONU types. The Sup_Mod field is also included to define an ONU's Quadrature Amplitude Modulation (QAM) efficiency.

New to the Downstream (DS) frame header is the SubCarrier Allocation identifier, SCA, field used by the OLT to distinguish between DSCA and SDSCA operation. It should be stressed out that in D4.2 [2] Fixed-SCA (FSCA) operation has also been included as an option of the SCA field. FSCA does not impose a requirement in dynamicity and as a result bandwidth allocation is restricted to the fixed assignment of subcarriers to ONUs. The Low_SC and High_SC fields are adequate to serve exactly that purpose. Other than that there is not a requirement for an algorithm exploiting SLA and CoS. To extent to dynamicity, it is required to define the subcarriers allocated to a user as well as the starting point in time and finishing point in time by means of time slots over which specific subcarriers are utilised by specific users. The LSC_Start_Time and HSC_Start_Time fields are introduced for that purpose alongside the Low_SC and High_SC. The modifications to the frame formats to incorporate these functionalities have been the extensive study of D4.2 [2].

2.3. NETWORK DEPLOYMENT SCENARIOS

The network reach, splitting ratios and as a result supported ONUs, the subcarrier number and aggregate data rates have been accounted for to establish a number of promoted scenarios for OFDMA-PON deployment. The specified parameters have provided inputs to OPNET for the development of the process models for network implementation. These network scenarios have been supported in their evalaution by algorithms using the criteria above.

The Urban scenario assumes a completely passive, 20 km reach, access network for densely populated areas. A high-splitting ratio of 256 ONUs per wavelength is the target (with 256 subcarriers as specified) with an overall capacity of 100 Gbps per wavelength, providing a guaranteed bit rate of 400 Mbps per residential user. Scenarios involving fewer ONUs could also be considered to accommodate higher bandwidth requests per ONU, as it would be the case for example in the presence of ONU/Base Stations (BSs).

The Passive Extended Reach scenario increases the network span to 40 km with no amplification at the Outside Plant (OSP), targeting network consolidation in metro-regional areas as well as wider coverage for rural areas. The supported ONUs number in this scenario is expected to be decreased, offering higher bandwidth per ONU (625 Mbps for 40 Gbps aggregate capacity per wavelength) through a 1:64 splitting ratio, maintaining the number of subcarriers to 256.

Finally, the Active Extended Reach scenario targets rural and special network consolidation architectures. Signal amplification is expected at Level 1 RN allowing for the maximum reach of 100 km. However, depending on the exact deployment specifications, it could take place at a remote CO. This scenario is expected to draw quite diverse packet delay and network throughput figures compared to any other implementation and is best suited to explore network migration scenarios.

2.4. DEVELOPMENT OF ALGORITHMS FOR DYNAMIC BANDWIDTH ALLOCATION

The ACCORDANCE MAC accounts for alternative modes of subcarrier utilization for intra-segment bandwidth allocation based on the adaptation of both G-PON and EPON-based protocols and algorithms. D4.1 [10] and its most recent update, D4.4 [1] have adequately justified the rationale in support of the use of DSCA, where ONUs benefit from the allocation of whole subcarrier/s, the SDSCA and the RDSCA modes of operation, where subcarriers are augmented between ONUs in the time domain. In the former case of hybrid OFDMA/TDMA bandwidth allocation, adjacent subcarriers are used for each ONU with the starting and finishing times being arbitrary. RDSCA performs the assignment of bandwidth per ONU in rectangular shapes (similarly to the RDSCA mode in D4.2), i.e. subcarriers are adjacent and start/finish times are equal in all cases. The only difference compared to RDSCA as defined in D4.2 [2], is that hereby a fixed scheduling window is not considered. This is due to the fact that RDSCA employs online scheduling to improve dynamicity.

Although at first glance the OFDMA-PON MAC bears many similarities to a hybrid WDM (Wavelength Division Multiplexing)/TDMA PON employing dynamic wavelength allocation, there are several fundamental differences between the two. While in WDM/TDMA PONs [11] each ONU can send/receive only at a specific wavelength at a given point in time, in OFDMA-PONs a multiplicity of subcarriers is available for each ONU in both directions. Furthermore, the typical case in OFDMA-PONs is that the bitrate of each subcarrier is much lower than that of a single wavelength - as well as that of the average ONU rate. This suggests on the one hand that in OFDMA-PONs several subcarriers have to be grouped together in order to offer the required bandwidth to each ONU and, more importantly, that the exact number of subcarriers selected impacts the QoS offered (e.g. if only few low-bitrate subcarriers are selected, the resulting delay may be restrictive). All those issues are handled appropriately in the course of the chapters, coming up with algorithms which decide dynamically on the scheduling of ONU transmissions based on their temporal bandwidth needs and the existing traffic conditions. The operation principles and complexity of the proposed algorithms are discussed in detail and ways to facilitate their implementation are proposed.

D4.4 [1] has presented selected preliminary designs of the ACCORDANCE MAC by including the simulator parameters of event-driven packet-based OPNET models and initial algorithms for the GPON-based DSCA and SDSCA bandwidth allocation based on non-status reporting. Network evaluations of all protocols and algorithms developed so far in the course of the project, including those in D4.4 though, will be performed for the first time in the current deliverable.

D4.3 will provide a complete overview of network performances for the DSCA, SDSCA and RDSCA algorithms, will extend their features to include CoS differentiation and will also present their upgrades to capitalize on bandwidth allocation over long-reach OFDMA-PONs. The requirements in further increasing network granularity and flexibility, by means of adaptive QAM modulation of subcarriers and how such a scheme can be applied in the form of cross-layer assignment algorithms, will be also included in the current deliverable.

3. Dynamic subcarrier allocation (DSCA) Algorithm

3.1. MONITORING MECHANISM

The first mechanism developed for bandwidth allocation in DSCA was based on a *monitoring* approach, where ONUs avoid the use of a conventional *report* mechanism to inform the OLT about their requirement in subcarriers. Instead, the transmission time is divided by the OLT into monitoring windows, in the period of which, the utilization of subcarriers for each ONU is monitored [12]. A diagram of the monitoring methodology and parameters of importance for its implementation are shown in Figure 2, including also the initial state of the algorithm subcarrier allocation process.

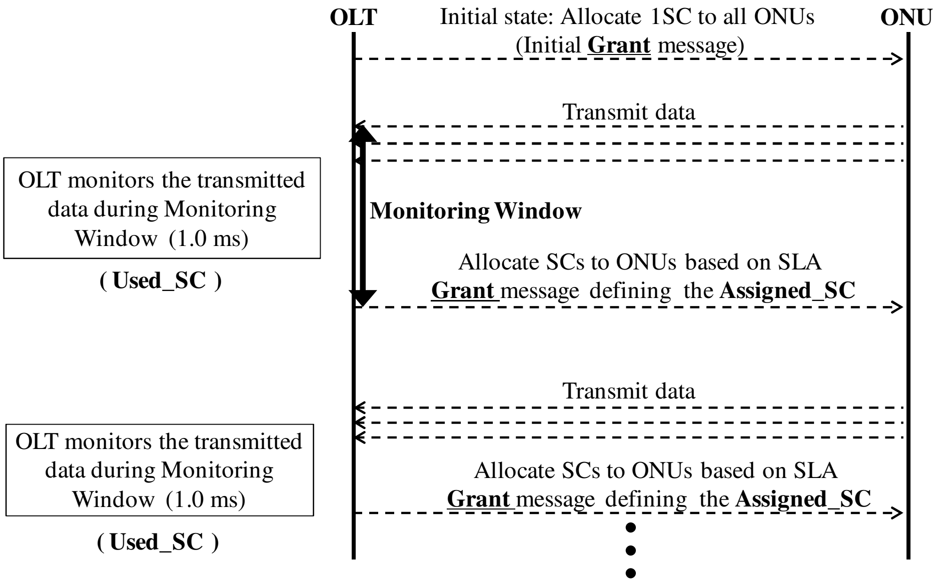

Figure 2: Monitoring mechanism.

The diagram projects the variation expected in packet delay between the *monitoring* scheme, exhibiting continuous transfer of ONU data, and *grant/reporting* in the traditional, hand-shake approach. The latter will require the elapse of three propagation delays for data transmission in contrast to one with *monitoring,* independently of the ONU queuing status. This characteristic offers *monitoring* an advantage especially at high offered load network traffic, with ONU queues expectedly full. With *grant/reporting* in the typical hand-shake approach, ONUs still have to wait for the reporting process to be completed although the OLT is aware of the need for full resource allocation. Following the continuous data transfer of ONUs as a result of *monitoring* the OLT automatically assigns the maximum possible number of subcarriers specified at individual ONU SLA profiles to ONUs, capitalising on performance at high traffic load.

The bandwidth allocation mechanism with *monitoring* assumes two possible scenarios [13]. In *Scenario 1*, if the subcarriers allocated in the immediately previous window to an ONU are not fully utilized, the OLT predicts that the already given subcarrier number is adequate or needs to be reduced. Consequently, the OLT subtracts the monitored subcarriers used (*Used_SC*), in a given window, from the allocated subcarriers in the previous window and releases the remaining to be utilized elsewhere in the network. Figure 3 represents *Scenario 1* as applied for ONU 2. During the N^{th} monitoring window ONU 2 profited by the allocation of 5 subcarriers, although only 2 subcarriers were practically utilized [13].

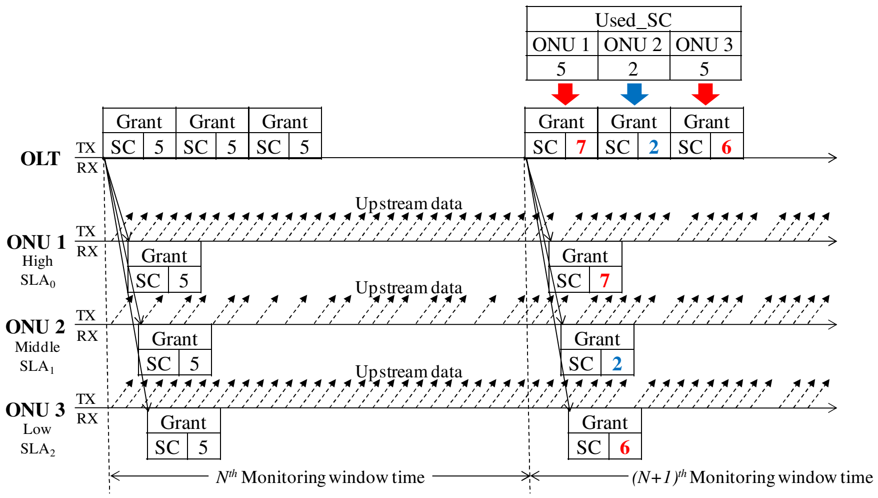

Figure 3: Example of DSCA transmission with Monitoring mechanism [13]

As a result the OLT will end up reducing at monitoring window *(N+1)* the subcarriers to be allocated to ONU 2 releasing three additional subcarriers to the network. In *Scenario 2* [13], the OLT monitors bandwidth transmission equivalent to full utilization of the previous window's allocation process, as envisaged by an ONU's full queue. In such scenario the OLT proceeds by assuming that an increase in that ONU's allocated subcarriers reflects more accurately its bandwidth requirements. This is achieved by distributing the subcarriers deposited from *Scenario 1* ONUs to *Scenario 2 ONUs* at strict SLA priority. This is exhibited in Figure 3 by ONUs 1 and 3. The higher the SLA assignment of an ONU the bigger the number of subcarriers they are been reallocated if required.

3.1.1. DSCA Flowchart

The flowchart used for the implementation of the DSCA monitoring algorithm is displayed in Figure 4, explaining the individual conditions for subcarrier utilization as well as defining all parameters [13].

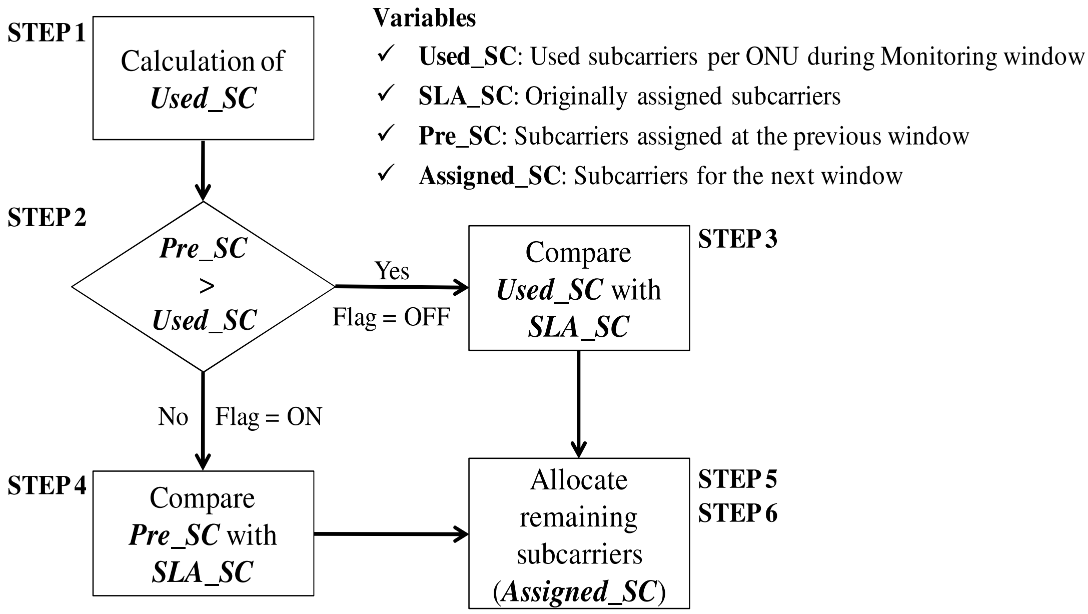

Figure 4: Flowchart of DSCA algorithm with monitoring.

The algorithm assumes that for each ONU an electronically imposed equalization delay is applied and, as a result, the OLT can consider them all located at the same distance, similarly to GPONs. The flowchart of the DSCA algorithm consists of the following steps:

STEP 1: By the end of each window, the OLT calculates the average subcarriers used per ONU during the preceded monitoring window time.

STEP 2: As a result ONUs are partitioned into two groups; the overperforming and underperforming ONUs:

- overperforming group: *Pre_SC = Used_SC*.
- underperforming group: *Pre_SC < Used_SC*.

STEP 3: (for underperforming group from STEP 2): The OLT compares *Used_SC* with *SLA_SC* using different reference subcarriers to distinguish SLA grades as applied for ONU 2 at Figure 3. The following cases are considered:

- If *Used_SC* is smaller than or equal to *SLA_SC*, then the OLT defines *Assigned_SC* based on the *Used_SC*, subtracts *Used_SC* from *SLA_SC* and assigns the difference to the group of "remaining subcarriers".
- If *Used_SC* is greater than *SLA_SC*, then the OLT defines *Assigned_SC* equal to *SLA_SC* because it is not aware at this stage if there are "remaining subcarriers".

STEP 4: (for overperforming group from STEP 2): The OLT compares *Pre_SC* with *SLA_SC* without considering the *Used_SC* since it has already determined in STEP2 that ONUs require more subcarriers as applied for ONU 1 and 3 at Figure 3. The additional subcarrier allocation is performed as follows:

- If *Pre_SC* is smaller than *SLA_SC*, then the OLT increments *Pre_SC* by 1 (*Pre_SC* + 1) and allocates it to *Assigned_SC*. Then it subtracts *Assigned_SC* from *SLA_SC* and assigns this difference to the "remaining subcarriers".
- If *Pre_SC* is greater than or equal to *SLA_SC*, then the OLT defines *Assigned_SC* equal to *SLA_SC* because it is unaware at this stage if "remaining subcarriers" are available.

STEP 5: After completing STEPs 2, 3 and 4 the OLT gathers the "remaining subcarriers" from the first case of STEP 3 and STEP 4 and distributes them to requesting ONUs based on their SLA priority.

STEP 6: Following STEP 5 if there are "remaining subcarriers" the OLT assigns them to ONUs based on SLA priority.

3.1.2. Network Simulation and Performance Evaluation

The simulation model exhibits an OFDMA-PON composed of one OLT and 32 ONUs, spanning over 40 km. Three SLA types, SLA_t, t=0, 1, 2, from high to low superiority have been considered. The number of ONUs in each service level is set to 2, 10 and 20 with the buffer size of each ONU limited to 10 MBytes. The total upstream data capacity is 10 Gbps, arranged in 64 subcarriers of 156.25 Mbps each. In addition, the guaranteed bandwidth for each SLA from high to low is specified at 468.75 Mbps, 312.5 Mbps and 156.25 Mbps respectively. Grant processing and propagation delays are 0.5 μs and 0.5 μs/km respectively. The network traffic is implemented by a Pareto self-similar traffic 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 simulation parameters required for data link layer modeling and protocol evaluation are summarized in Table 1 below alongside, CoS differentiation and traffic generation.

Table 1: Example of DSCA design parameters.

<table>
<tr><th>Parameters</th><th colspan="2">description</th></tr>
<tr><td>Total network capacity</td><td colspan="2">10 Gbps</td></tr>
<tr><td>Number of subcarriers</td><td colspan="2">64</td></tr>
<tr><td>Data rate per subcarriers</td><td colspan="2">156.25 Mbps (10 Gbps / 64)</td></tr>
<tr><td rowspan="2">Number of ONUs</td><td colspan="2">32</td></tr>
<tr><td colspan="2">SLA0 : SLA1 : SLA2 = 2 : 10 : 20</td></tr>
<tr><td rowspan="3">Guaranteed Data Rate per SLA (SLA_SC)</td><td>SLA0</td><td>468.75 Mbps</td></tr>
<tr><td>SLA1</td><td>312.5 Mbps</td></tr>
<tr><td>SLA2</td><td>156.25 Mbps</td></tr>
<tr><td>Distance between OLT and ONU</td><td colspan="2">40 km</td></tr>
<tr><td>Monitoring window time</td><td colspan="2">2.0 ms</td></tr>
<tr><td>Grant processing delay</td><td colspan="2">5 μs</td></tr>
<tr><td>Propagation delay</td><td colspan="2">5 μs/km</td></tr>
<tr><td>ONU offered load 1.0</td><td colspan="2">312.5 Mbps (10 Gbps / 32)</td></tr>
<tr><td>Network offered load 1.0</td><td colspan="2">10 Gbps</td></tr>
<tr><td>Packet size</td><td colspan="2">64 – 1518 Bytes
(Uniformly generated)</td></tr>
<tr><td rowspan="3">Traffic generation of CoSs</td><td colspan="2">High priority CoS0: 20 %</td></tr>
<tr><td colspan="2">Middle priority CoS1: 40 %</td></tr>
<tr><td colspan="2">Low priority CoS2: 40 %</td></tr>
</table>

Figure 5 (a) confirms that the end-to-end packet delay of high and middle priority SLAs is less than 1.4 ms, even if the ONU offered load is 1.0. This is because the guaranteed bandwidth of the high and middle SLAs are greater than or equal to the ONU offered load of 1.0 corresponding to 312.5 Mbps. In addition, the DSCA algorithm allocates the remaining subcarriers according to the SLA priority. As expected, the end-to-end pack delay of low priority SLAs dramatically increases at an ONU offered load of 0.7 since DSCA on its own cannot support granularity and further subcarrier distribution among low bandwidth ONUs. Figure 5 (b) represents the end-to-end packet delay according to three CoS profiles under SLA_0 to establish the priority insights for the various service classes accessing the network, at conditions of high bandwidth transfer. It is worth pointing out that the packet delay of the high priority traffic, CoS_0 is less than 1.0 ms, a very promising figure considering it is reported at 40 km link spans and the capability such a figure offers to ACCORDANCE to support the stringiest of requirements of its various backhauled technologies. Additionally the observed trace, compared to the remaining classes, displays a trend at the right direction since CoS_0 is expected to depart ONU queues with high priority. Similar characteristics were also recorded for SLA_1 and SLA_2.

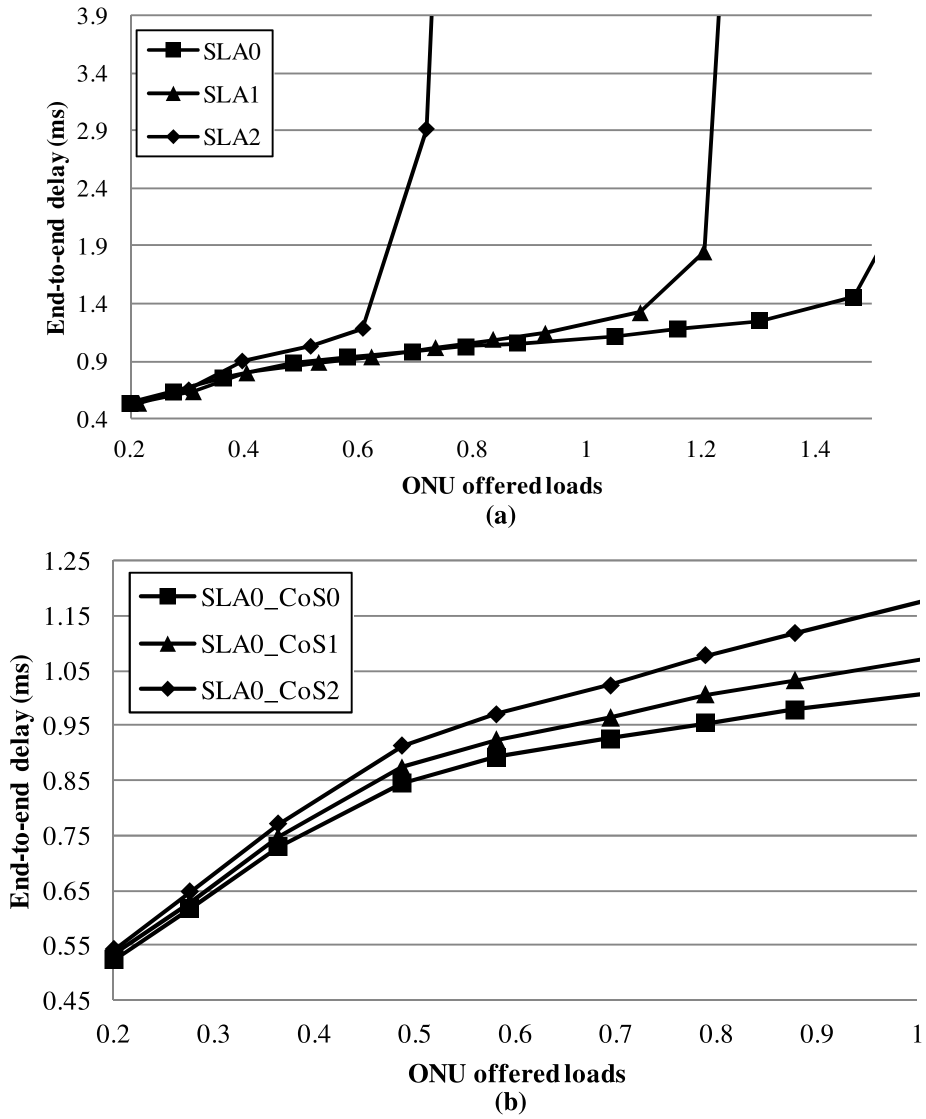

Figure 5: End-to-end delay according to (a) three SLAs (b) three CoS grades under SLA_0.

Figure 6 (a) shows the total network throughput as a function of the network load, confirming a very efficient utilization of the network capacity. In more detail Figure 6 (b) displays the throughput achieved per SLAs as a function of the ONU offered load rather than the network load. The saturated throughputs displayed are at 600 Mbps, 460 Mbps and 200 Mbps corresponding to the high to low SLAs respectively.

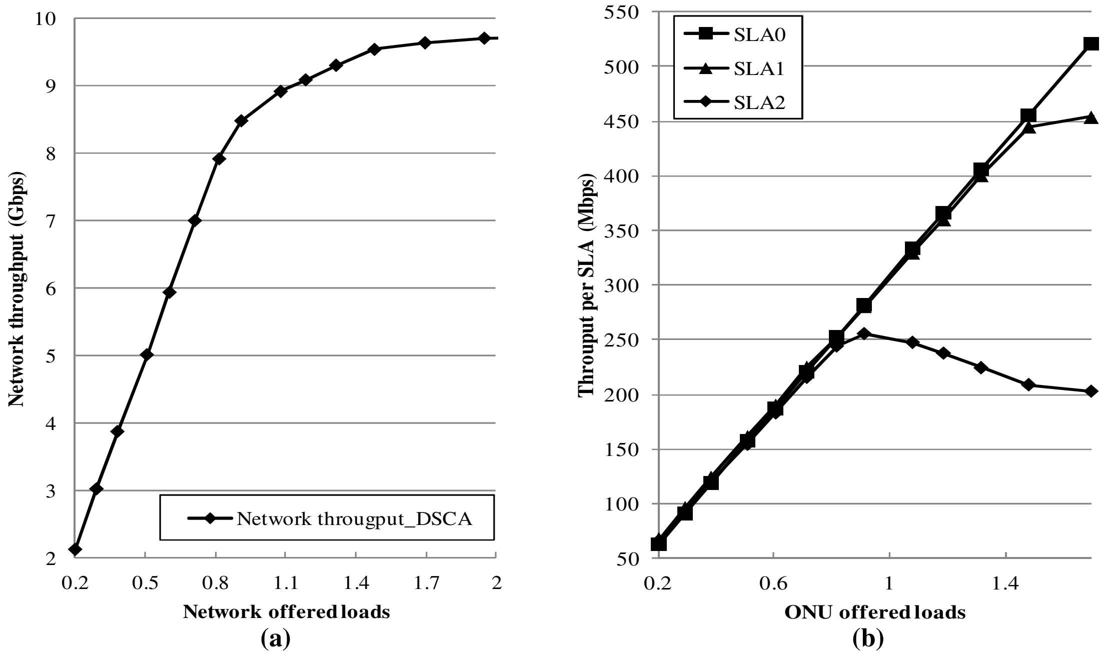

Figure 6: (a) Total network throughput and (b) network throughput per SLA

These values are higher in each case than the guaranteed bandwidths specified in Table 1. There are two reasons contributing to this observation. This first being the accurate distribution of subcarriers to ONUs by the protocol and their utilisation at full capacity. The second reason is the availability of spare subcarriers (out of the 64 subcarriers, 46 subcarriers are assigned to ONUs based on their SLA). The OLT has monitored full utilisation of assigned subcarriers to individual ONUs and has opted to assign extra subcarriers for potentially benefiting ONUs from higher bandwidth transmission. Hence the additional Mbps above the guaranteed bandwidths in each case. The remaining 18 subcarriers are distributed by the monitoring mechanism to ONUs based on the approach described by the algorithm steps. The observed behaviour highlights the limitation of the DSCA algorithm with respect to granularity since subcarriers cannot be shared in time and as a result the additional subcarriers may or may not be employed at their full capacity.

4. Development of Sequential Dynamic Subcarrier Allocation (SDSCA) Algorithms

4.1. MONITORING-BASED SDSCA ALGORITHM

4.1.1. SDSCA Algorithm Flowchart

The bandwidth allocation of the SDSCA mode is based on time slots for which subcarriers are assigned by the OLT to the ONUs. Both monitoring and grant/reporting scheduling are investigated with SDSCA, providing extensive performance figures and conclusions. An example can be seen in Figure 7. In this case, each ONU temporal bandwidth needs are estimated by the OLT during the time of a monitoring window. In a monitoring window the OLT allocates bandwidth according to the utilization of time slots, assigned to an ONU in the previous window. In that sense, if that ONU for example consumes 90 percent of the previous allocated bandwidth, the OLT determines that the queue statue of this ONU is busy and as a result increases its offered bandwidth by means of increased time slots. The number of additional time slots depends on the overall bandwidth requirements and ONU SLA. SDSCA takes into consideration various cases of subcarrier allocation to increase network flexibility and demonstrate the maximum possible capacity utilization by avoiding the formation of idle time slots. These cases are shown in Figure 7 and they will be dealt with below once the algorithm methodology has been described.

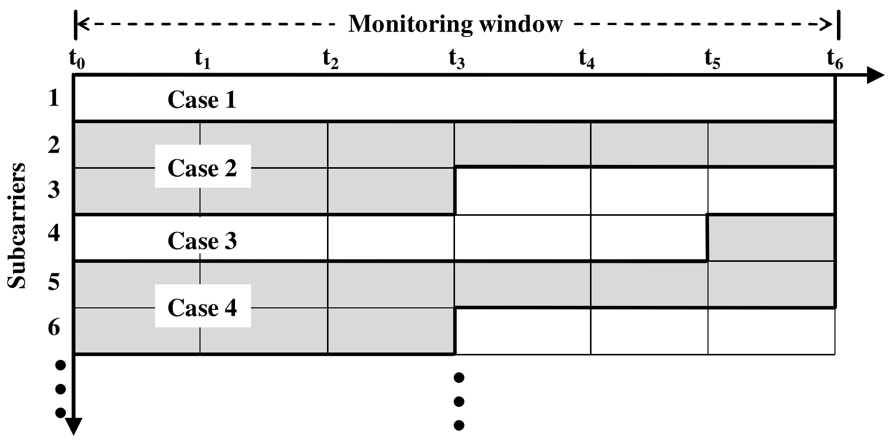

Figure 7: SDSCA bandwidth allocation based on monitoring scheme.

In harmony with the previous section, Figure 8 describes the new algorithm operation in the form of a flow chart.

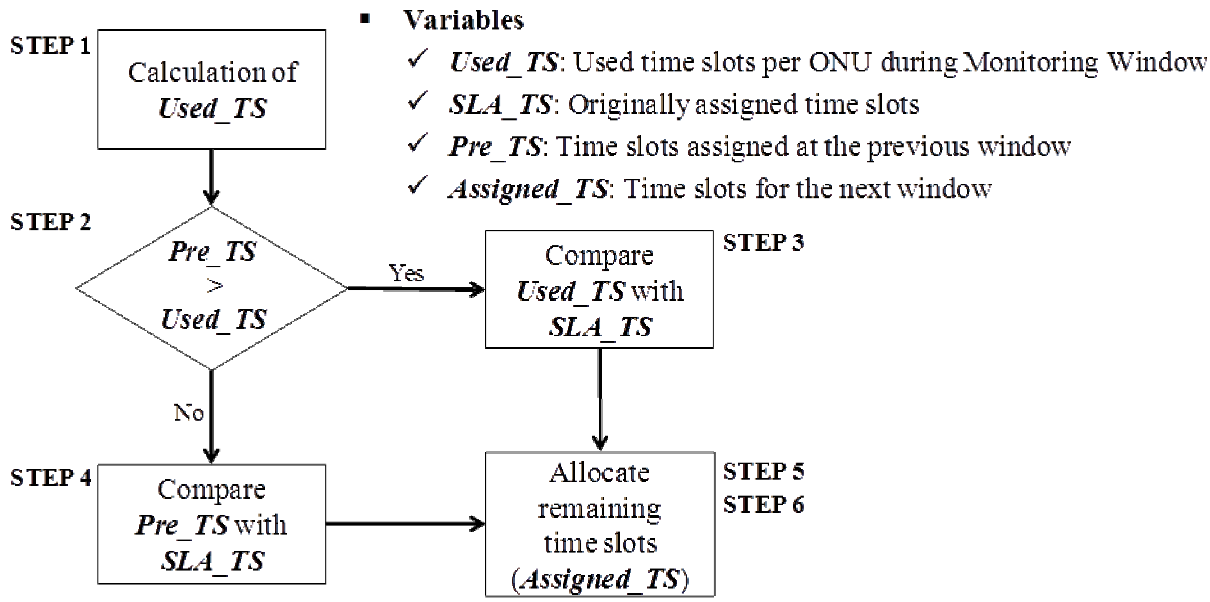

Figure 8: Flowchart for the proposed SDSCA algorithm.

<u>*STEP 1*</u>: By the end of each window, the OLT calculates the average time slots used per ONU during the preceded monitoring window time.

<u>*STEP 2*</u>: As a result ONUs are partitioned into two groups; the *overperforming* and *underperforming* ONUs:

- *overperforming* group: *Pre_TS* = *Used_TS*.
- *underperforming group: Pre_TS* < *Used_TS.*

<u>*STEP 3*</u> (*underperforming* group from *STEP* 2): The OLT compares *Used_TS* with *SLA_TS* using different reference time slots to distinguish SLA grades. The following cases are considered:

- If *Used_TS* is smaller than or equal to *SLA_TS*, then the OLT defines *Assigned_TS* based on the *Used_TS*, subtracts *Used_TS* from *SLA_TS* and assigns the difference to the group of "remaining time slots".
- If *Used_TS* is greater than *SLA_TS*, then the OLT defines *Assigned_TS* equal to *SLA_TS* because it is not aware at this stage if there are "remaining time slots".

<u>*STEP 4*</u> (*overperforming* group from STEP 2): The OLT compares *Pre_TS* with *SLA_TS* without considering the *Used_TS* since it has already determined in STEP2 that

ONUs require more time slots. The additional time slot allocation is performed as follows:

- If *Pre_TS* is smaller than *SLA_TS*, then the OLT increments *Pre_TS* by 2 (high priority SLAs, *Pre_TS* + 2) or by 1 (middle and low priority SLAs, *Pre_TS* + 1) and allocates it to *Assigned_TS*. *Assigned_TS* should be less than or equal to *SLA_TS*. Then it subtracts *Assigned_TS* from *SLA_TS* and assigns this difference to the "remaining time slots". A note should be made that the *Pre_TS* increase specified here has been the outcome of optimizing the algorithm performance for different number of increments per SLA.
- If *Pre_TS* is greater than or equal to *SLA_TS*, then the OLT defines *Assigned_TS* equal to *SLA_TS* because it is unaware at this stage if "remaining time slots" are available.

STEP 5: After completing STEPs 2, 3 and 4 the OLT gathers the "remaining time slots" from the first case of STEP 3 and STEP 4 and distributes them to requesting ONUs based on their SLA priority.

STEP 6: Following STEP 5 if there are "remaining time slots" the OLT assigns them to ONUs based on SLA priority.

A Pseudo-code representation of the monitoring SDSCA algorithm is also shown in Figure 9.

Set variables, *i* is the index of ONU

TS_i^{Used} is the used time slots per ONU during monitoring window.

TS_i^{SLA} is the guaranteed time slots according to SLA levels.

TS_i^{Pre} is the time slots assigned at the previous window.

TS_i^{Assign} is the time slots for the next window.

$TS^{remaining}$ is the remaining time slots.

$TS_s^{increase}$ is the increment time slots according to SLA, s is the index of SLA

Calculate TS_i^{Used} during the monitoring window time
For (Number of ONUs) **do**
    If $TS_i^{Pre} > TS_i^{Used}$ **then** *//underperforming group*
        If $TS_i^{Used} > TS_i^{SLA}$ **then**
            $TS_i^{Assign} = TS_i^{SLA}$
        Else
            $TS_i^{Assign} = TS_i^{Used}$
            $TS^{remaining} = TS^{remaining} + (TS_i^{SLA} - TS_i^{Used})$
        End If
    Else *//overperforming group*
        If $TS_i^{Pre} > TS_i^{SLA}$ **then**
            $TS_i^{Assign} = TS_i^{Used}$
        Else
            $TS_i^{Assign} = TS_i^{Pre} + TS^{remaining}$
            $TS^{remaining} = TS^{remaining} + (TS_i^{SLA} - TS_i^{Assign})$
        End If
    End If
End do

For (Number of ONUs) **do**
    If $i \in \{overperforming$ group$\}$ **then**
        $TS_i^{Assign} = TS_i^{Assign} + TS_s^{increase}$
        $TS^{remaining} = TS^{remaining} - TS_s^{increase}$
    End If
End For

While $TS^{remaining} > 0$ **then**
    For (From the ONU with high priority SLA) **do**
        $TS_i^{Assign} = TS_i^{Assign} + 1$
        $TS^{remaining} = TS^{remaining} - 1$
    End For
End While

Figure 9: Pseudo code for monitoring-based SDSCA.

Following the allocation of the required number of time slots, explained in Figures 8 and 9, subcarriers are assigned to ONUs by the OLT to accommodate the assigned time slots. The Grant messages communicated to ONUs in that instance distinguish between the four following cases. These are displayed in Figure 7.

Case 1: ONUs do not share subcarriers with other ONUs. For example, if each subcarrier is divided into 6 time slots and the total time slots allocated to an ONU after STEP 6 of the algorithm above is a multiple of 6, the specific ONUs use whole subcarrier/s.

Case 2: The *Requisite Subcarriers* and *Scheduled Subcarriers* are equal and the index of time slot is 0 (t_0 at Figure 7). 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 based on availability and scheduling status. For example, if an ONU is allocated 13 time slots and there are 6 time slots into each subcarrier, the number of *Requisite Subcarriers* is 3.

Case 3: The *Requisite Subcarriers* is equal to the *Scheduled Subcarriers* and the index of time slot is not 0 (t_1 – t_5 at Figure 7).

Case 4: The *Requisite Subcarriers* is less than the *Scheduled Subcarriers*. Since the number of allocated time slots is 10, the *Requisite Subcarriers* are 2 but 3 *Scheduled Subcarriers* are assigned to that ONU due to time slot unavailability and scarce distribution.

The way data transfer is implemented for each of these cases, once the grant messages have been received by the ONUs, is illustrated as an example in Figure 10. It is assumed the total upstream capacity of 10 Gbps, the number of subcarriers 64, the number of ONUs 32 and each subcarrier is divided into 6 timeslots. In *Case 1*, ONUs transmit 156.25 Mbps data during a monitoring window time (156.25 Mbps = 10 Gbps/64 subcarriers). In *Case 2*, ONUs transmit at two different data rates, 312.5 Mbps using two subcarriers until t_3 and 156.25 Mbps using one subcarrier until t_6. In *Case 3*, ONUs use three different data rates, 156.25 Mbps with one subcarrier until t_3, 312.5 Mbps with two subcarriers until t_5 and 156.25 Mbps with one subcarrier until t_6. In Case 4, ONUs also use three different data rates, 312.5 Mbps until t_3, 156.25 Mbps until t_5 and 312.5 Mbps until t_6.

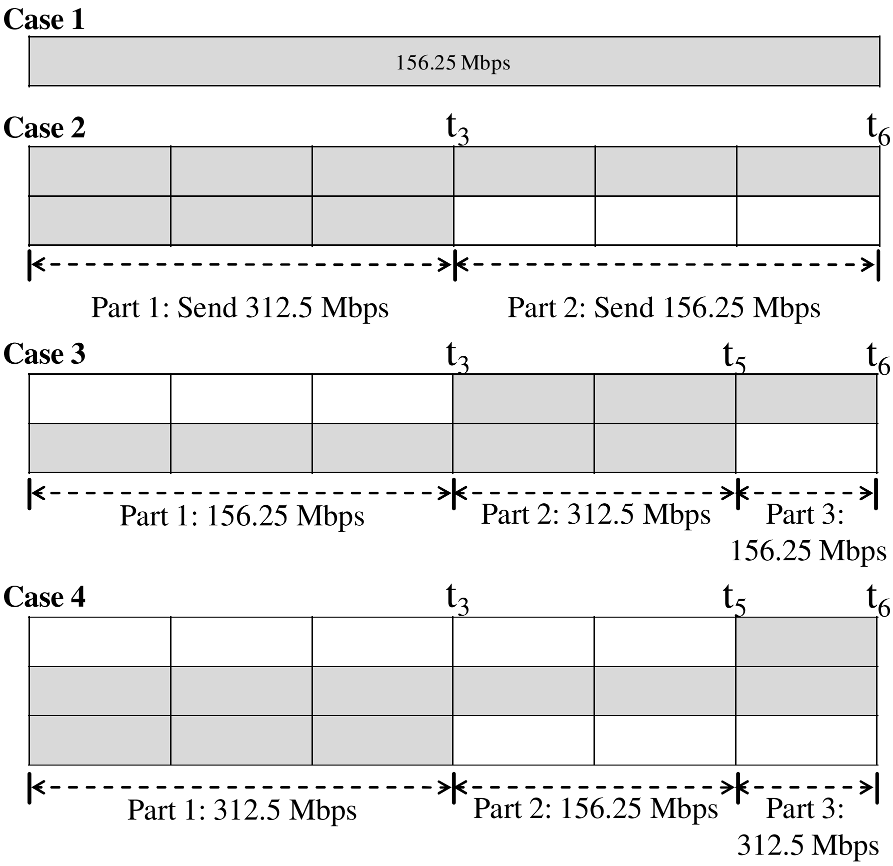

Figure 10: Example of data transfer rates of ONUs per case.

4.2. GRANT/REPORTING BASED SDSCA ALGORITHM

This section describes the characteristics of the reporting-based SDSCA algorithm. The algorithm performs bandwidth allocation incorporating three queue priorities to simulate three classes of traffic. Each ONU communicates information to the OLT about all three of its queue priorities using the same REPORT message. The OLT calculates the grants for each ONU for each class priority, 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. This Grant/Reporting mechanism suggests that every ONU is polled periodically in a burst manner [14]. All gate messages should be sent to each ONU at the specified time in a burst fashion. Thus, the algorithm can benefit delay sensitive services, enhancing QoS since the next polling time for each ONU can be predicted. In addition, the algorithm does not consume downstream bandwidth by frequently polling the ONUs under the light-payload. Each REPORT consists of three messages corresponding to the BE, AF, and EF classes queue sizes with EF traffic served first, followed by AF and last the BE class.

To proceed with the analysis of the bandwidth allocation principles, 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, as standard in all ACCORDANCE developed algorithms, and manages as 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 is defined respectively by,

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

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

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

$$B_{total}^{req} = \sum_{i=1}^{N} B_i^{req} \tag{3}$$

Each bandwidth requirement of each ONU includes information for all three of its queues as given in eq. (4).

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

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

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

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 light-loaded ONUs. When $B_s^{grt} < B_i^{req}$, a surplus bandwidth, $B_i^{surplus}$, is allocated to the i-th ONU, as follows,

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

In eq. (6) *K* is the set of heavily loaded ONUs. Finally the algorithm distributes evenly the surplus bandwidth among these heavily loaded ONUs using the equation below.

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

To provide a graphical representation of scheduling in the reporting-SDSCA algorithm, a flowchart is shown in Figure 11.

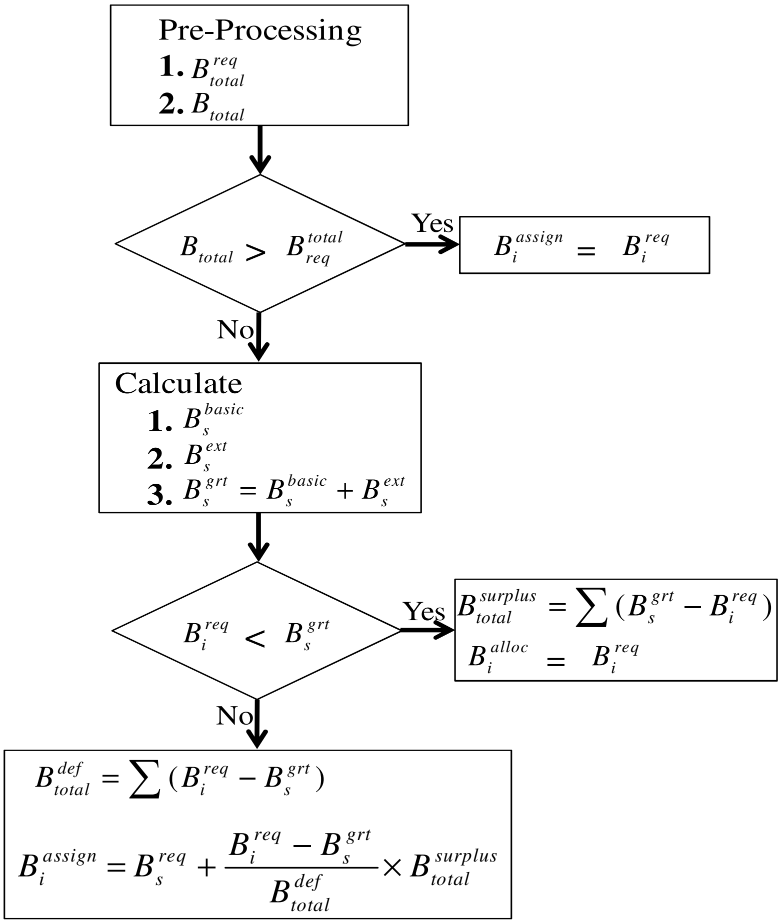

Figure 11: Flowchart of the reporting-based SDSCA algorithm.

4.3. MONITORING AND REPORTING-BASED SDSCA ALGORITHMS PERFORMANCE EVALUATION

4.3.1. OPNET simulation parameters

To evaluate the proposed algorithms in terms of the network throughput, end-to-end packet delay and packet loss rate, OPNET simulations were developed in each case, exhibiting an OFDMA-PON composed of one OLT and 32 ONUs. In comparison to the DSCA algorithm network, the distance between the OLT and each ONU is maintained at 40 km to establish the performance figures of the algorithms at distances of substance to NGPONs coverage, likewise ACCORDANCE. Three SLAs, SLAt, t=0, 1, 2, from high to low superiority have been considered. The number of ONUs in each service level is set to 2, 10 and 20 with the buffer size of each ONU limited to 10 MBytes. The total upstream data capacity is 10 Gbps, arranged in 64 subcarriers of 156.25 Mbps each. Grant processing and propagation delays are accounted for employing 0.5 μs and 0.5 μs/km, respectively. The network traffic is implemented by a Pareto self-similar traffic model as usual with a typical Hurst parameter of 0.8 to simulate practical network patterns. The packet size is uniformly generated between 64-1518 Bytes. For the grant/reporting mechanism, subcarriers are logically divided into four timeslots and the guard time between ONUs is set to 0.5 μs.

Similarly to the DSCA algorithm, the simulation model has accounted for class-of-service differentiation with CoS_0 to CoS_2, featuring high to low priority queues. To simulate a realistic OFDMA-PON model, 20% of the generated packets are assigned to CoS_0 and the rest 80% are averaged between CoS_1 and CoS_2.

4.3.2. Performance comparison

With respect to the network throughput measure, Figure 12 confirms superior performance of the monitoring based SDSCA, allowing at high network load values (defined as the ratio between the sum of each ONU loading and the network capacity), to increase up to around 8.9 Gbps, compared to the reporting based SDSCA that stalls at only 7.8 Gbps. As a result, apart from the 14.1% improvement in channel utilization rate, the measured 89% channel capacity figure displays network utilization comparable to the application of the reporting based DSCA although as expected inferior.

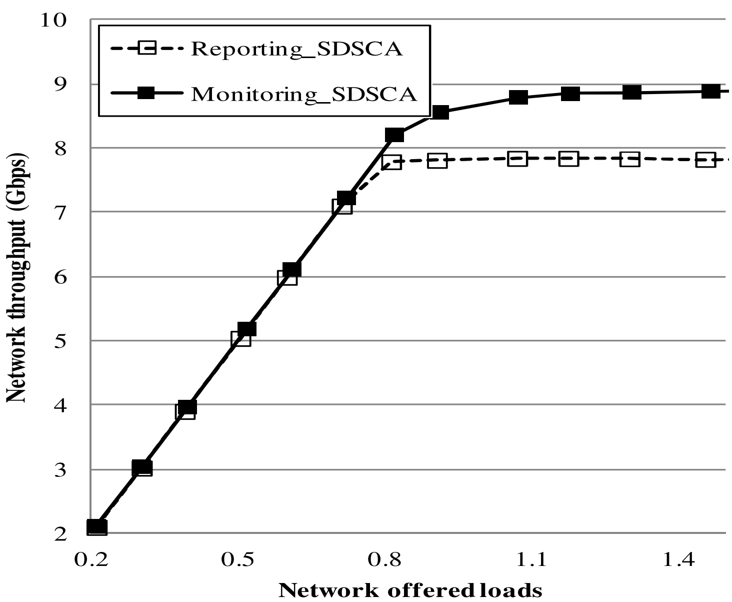

Figure 12: Comparison of network throughput between monitoring and reporting.

To investigate the data transfer quality, Figure 13 exhibits the end-to-end packet delay for all three SLAs versus ONU offered load, defining the proportion between each ONU loading and the simulated ONU capacity for each algorithm. It can be observed that the threshold ONU loadings for the reporting based SDSCA and monitoring based SDSCA to achieve low transmission delay are 0.50 and 0.70, respectively. These points confirm that in the worst case scenario, OFDMA-PONs with reporting based SDSCA and monitoring based SDSCA can provide low delay transmission when the overall network offered load is not in excess of 5.0 and 7.0 Gbps, respectively ([0.50 or 0.70] × 312.5 Mbps × 32 ONUs = 5.0 or 7.0 Gbps) for a 10 Gbps network. The 2.0 Gbps increment represent a 40% improvement in view of the monitoring based algorithm.

To elaborate further, the monitoring algorithm demonstrates significantly lower mean packet delay figures, exhibiting almost 5.1 and 3.0 times reduction at around 80% and 70% ONU loading for SLA_0 and SLA_2, respectively, and approximately seven times reduction at around 90% loading for SLA_1. It also becomes evident from this figure that the ONU offered load, before the packet delay reaches the 3 ms limitation for time-sensitive traffic, has been extended from 187.5 Mbps to 218.75 Mbps for SLA_2 ONUs. The gained 31.25 Mbps bandwidth for SLA_2 ONUs can be utilized to support additional multimedia services for each ONU, such as online gaming, education-on-demand, and video conferencing.

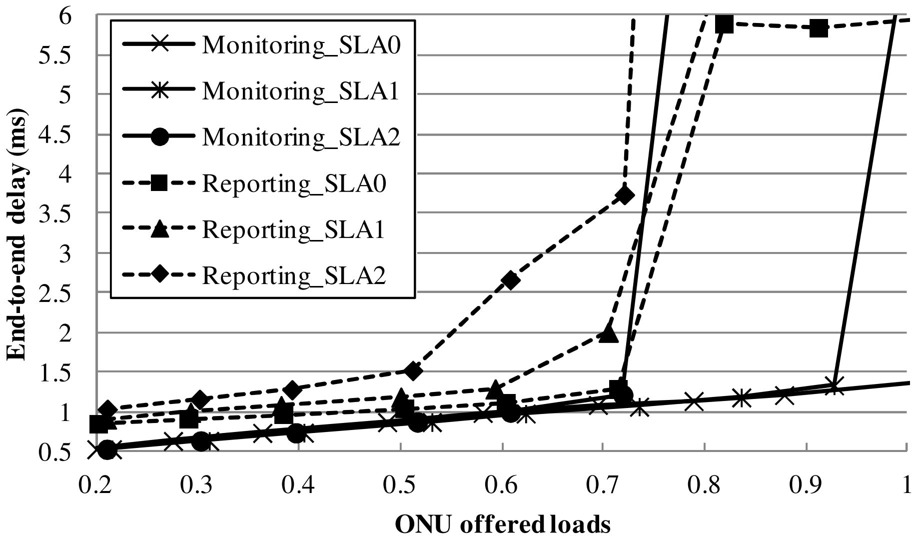

Figure 13: End-to-end packet delay.

Furthermore, as shown in Figure 14, the proposed schemes also provide considerable improvement in terms of packet loss rate versus network load. Comparing the responses of the two algorithms for the worst-case scenario, loss-free transmission is extended from 7.1 Gbps network loads (10 Gbps×0.71) with reporting to 8.2 Gbps (10 Gbps×0.82) with monitoring providing an extra 1.1 Gbps network capacity for ISPs, either to offer more real-time services to subscribers or support higher number of subscribers.

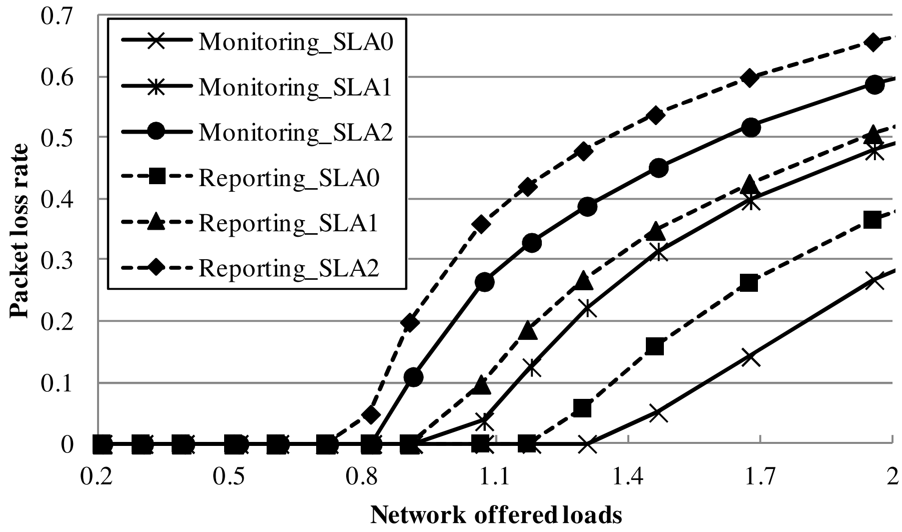

Figure 14: End-to-end packet delay with SLA

In addition, when ONUs receive their upstream bandwidth maps, the strict priority queue method could allow sequential delivery of CoS_0, CoS_1, and finally, CoS_2 traffic by means of high-priority queuing packets, e.g., CoS_0, accessing the network first. As a result, all traffic types are expected to benefit from sufficient transmission bandwidths under low network load, while experience buffering when the overall traffic exceeds the maximum network capacity with QoS as a reference measure. 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 for further increasing load.

To provide a direct figure of service level performance in the presence of CoS with regards to the recorded packet delay, Figure 15 exhibits CoS_0 traffic performance at all three SLAs with increasing ONU offered load for both the monitoring based SDSCA and reporting based SDSCA algorithms. A reduction by 1.5 times is presented at around 70% of the ONU offered load, demonstrating the ability of the monitoring algorithm to administrate congestion in the backbone network. In similarity with the profile for CoS_0 traffic, CoS_1, as shown in Figure 16, exhibits in view of the monitoring algorithm, very low packet delay for all three ONU service levels. A clear characteristic with almost 3 times reduction in delay is demonstrated for the least priority service level, SLA_2, between 281.25 and 312.5 Mbps of ONU offered load. Correspondingly, a twofold reduction in delay is also presented for SLA_0 and SLA_1 ONUs at around 85% of ONU load.

In comparison with CoS_0 and CoS_1 traffic, the time insensitive service 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 Figure 17, displaying significantly increased delay figures among the three service levels. In any case though the displayed delay in view of the monitoring algorithm is still significantly less than that observed with any other algorithm.

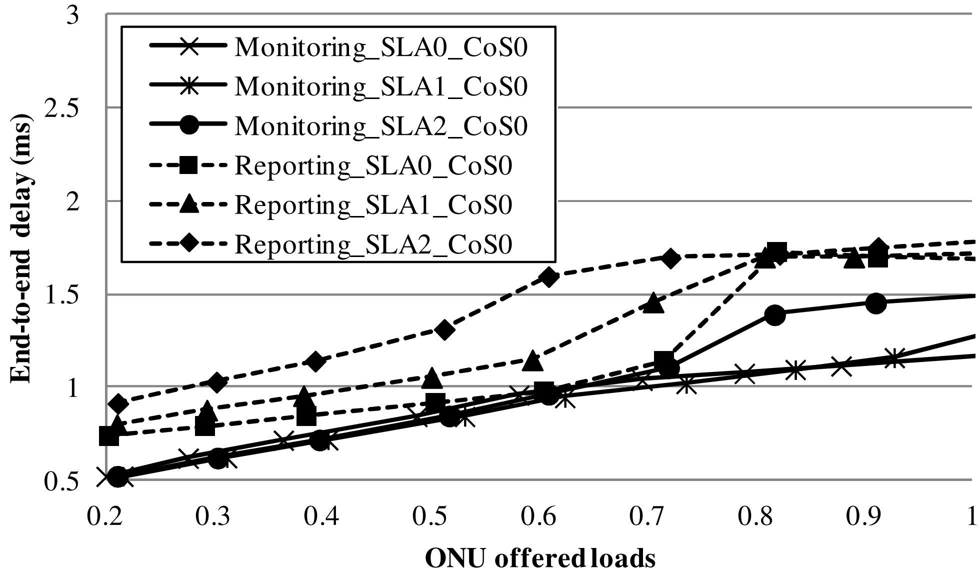

Figure 15: End-to-end packet delay for CoS_0.

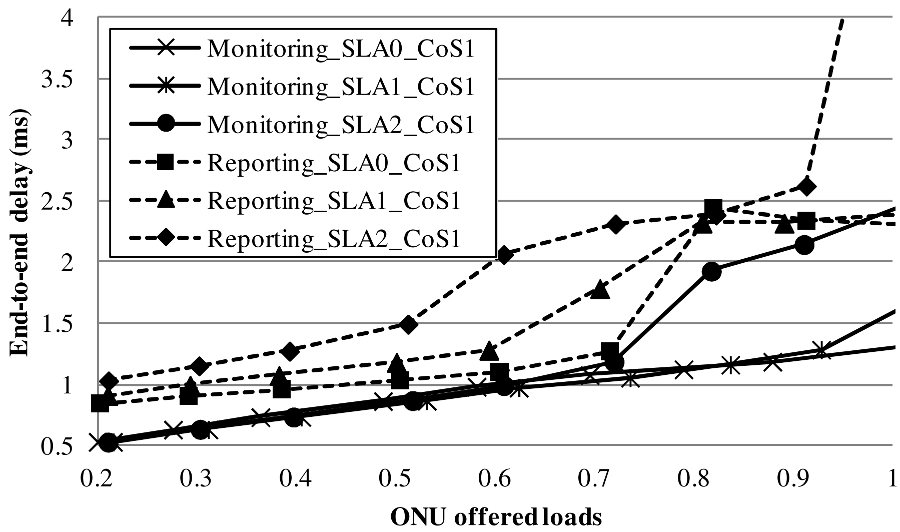

Figure 16: End-to-end packet delay for CoS_1.

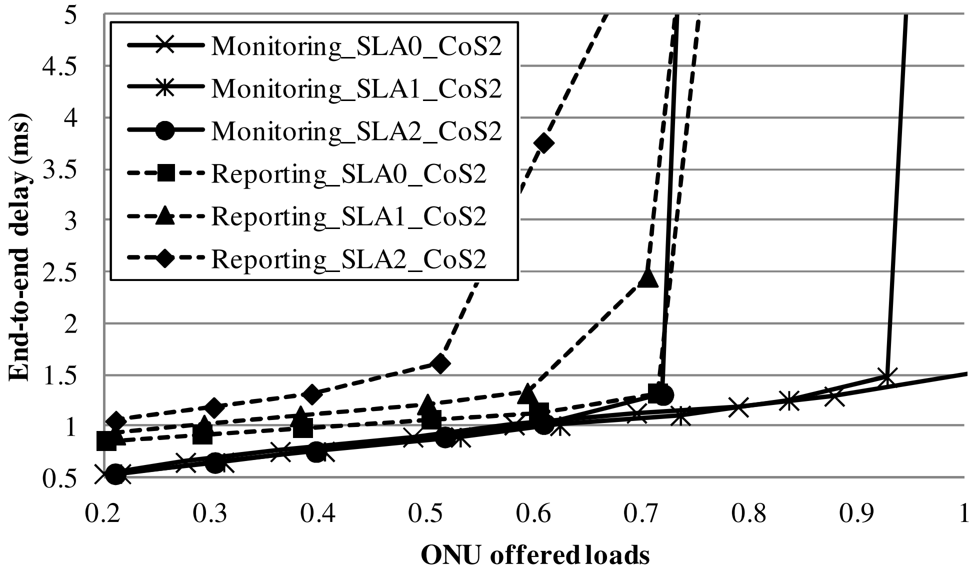

Figure 17: End-to-end packet delay for CoS_2.

Considering the traffic responses for SLA_2 ONUs to draw the worst case figures fir each algorithm, the monitoring based SDSCA presents roughly eight times reduction in packet delay for ONU loads ranging between 234.4 and 265.6 Mbps. Similarly, around 5-10 times decreased figures are observed for ONUs between 156.25 and 250 Mbps. In addition, the maximum ONU throughput in Figure 17 for CoS_2 is also extended from 162.5 and 185.37 Mbps in the reporting algorithm and to 230.75 and 287.5 Mbps for SLA_1 and SLA_2 ONUs with the monitoring algorithm. The significance of the reduced delay values for each SLA ONU in real network deployment scenarios is crucial since it represents 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.

Finally, in addition to mean packet delay, the network packet loss rate versus network load is another 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 monitoring algortihm. Subsequently, CoS_1 and CoS_2 traffic characteristics are presented in Figure 18 and Figure 19, respectively. For CoS_1 traffic, considering the worst-case scenario ONUs, the loss-free transmission is extended from 10.6 Gbps (10 Gbps×1.06) with the reporting algorithm to 11.8 Gbps (10 Gbps×1.18) with monitoring, providing an extra 1.2 Gbps network capacity.

Similarly, the loss-free transmission for the time-insensitive traffic, CoS_2, is still extended from 7.1, 9.0, and 10.6 Gbps to 8.2, 10.7, and 13.0 Gbps providing an extra 1.3, 1.7, and 2.4 Gbps network capacity for SLA_2, SLA_1 and SLA_0, respectively.

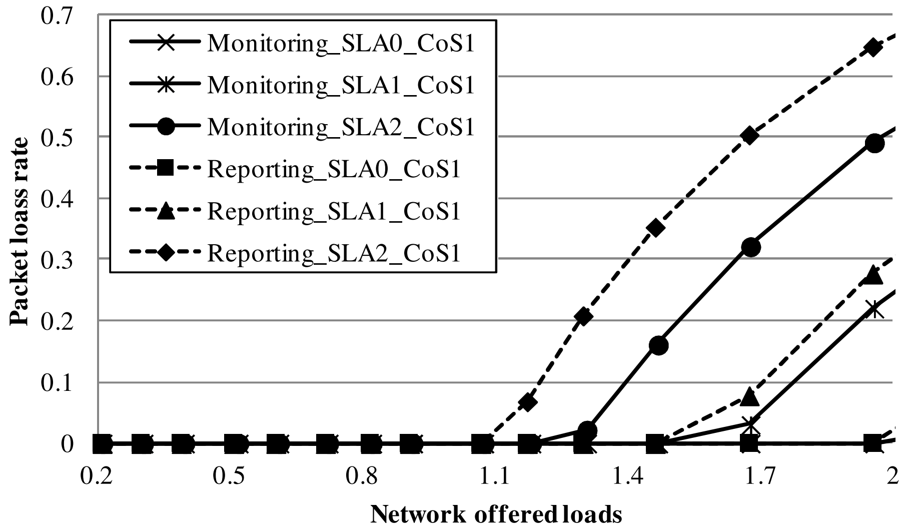

Figure 18: CoS_1 End-to-end packet delay with SLA.

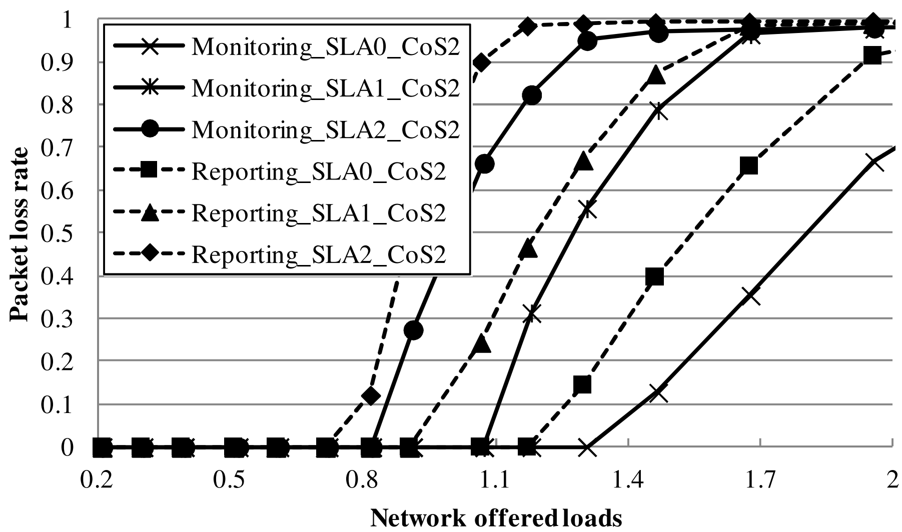

Figure 19: CoS_0End-to-end packet delay with SLA.

5. EPON-Based Scheduling Schemes

5.1. THE CONSIDERED MAC FRAMEWORK

5.1.1. Introduction

For the following discussion, an EPON-based MAC protocol is assumed, following the guidelines provided in Section 5 of Deliverable D4.2. In the considered framework, Status Reporting (SR) Dynamic Bandwidth Allocation (DBA) is performed using upstream *report* (conveying ONU queue status information to the OLT) and downstream *grant* (informing the ONUs about their assigned rectangles in the upstream) messages. As already mentioned, RDSCA performs the assignment of bandwidth for each ONU in rectangular shapes, where the subcarriers assigned to each ONU are adjacent and the start/finish times are equal in all cases.

It should be reminded that the benefits from RDSCA are multi-fold: First, the adjacency of subcarriers facilitates their selection by the ONU Rx in the downstream direction. Moreover, the use of frequency guard-bands around the assigned subcarrier groups in order to avoid interference among transmissions by multiple ONUs is minimized (the use of a large number of small subcarrier groups per ONU would result in increased bandwidth waste). Finally, the rectangular shape for the upstream in particular largely simplifies the MAC protocol since in the EPON-based context considered, only few extra fields (e.g. for the assigned low/high subcarrier) are additionally required in the Multi-point Control Protocol (MPCP) GATE messages. Figure 20 (taken from D4.2) depicts the modified IEEE 802.3av [9] GATE messages, allowing for rectangular DBA.

Note also that with respect to implementation, it is expected that a certain amount of the available subcarriers will also be employed for other purposes: Some are being used as pilot tones (to obtain channel state information), while others serve as guards to avoid interference with the DC component (zero power is employed in the latter). In addition, a dedicated set of subcarriers is reserved for carrying control message exchanges as described in Deliverable D4.2. For all further discussion though we will focus only on the *data subcarriers* and we will assume a contiguous indexing of them (although in reality they may be separated by non-data ones).

6	Destination Address	
6	Destination Address	
2	Length/Type = 0x8808	
2	Opcode = 0x0002	
4	Timestamp	
1	Number of grants/Flags	
0/4	Grant #1 Start time	
0/4	**Grant #1 Stop time**	*Modified field (replaces Length)*
0/1	**Grant #1 Low SC**	*New fields*
0/1	**Grant #1 High SC**	
0/1	**Grant #1 SCA**	
0/4	Grant #2 Start time	
0/4	**Grant #2 Stop time**	*Modified field (replaces Length)*
0/1	**Grant #2 Low SC**	*New fields*
0/1	**Grant #2 High SC**	
0/1	**Grant #2 SCA**	
0/4	Grant #3 Start time	
0/4	**Grant #3 Stop time**	*Modified field (replaces Length)*
0/1	**Grant #3 Low SC**	*New fields*
0/1	**Grant #3 High SC**	
0/1	**Grant #3 SCA**	
6-39	Pad/Reserved	
4	FCS	

Figure 20: Modified GATE MPCPDU.

5.1.2. *EPON-based DBA Algorithm Classification*

In order to facilitate algorithm descriptions, the overall DBA process in OFDMA-EPONs can be broken up into several distinct steps which could be summed up as the:

(a) Report handling

(b) Report reordering

(c) Grant scheduling

In step (a) there are two options, the *online* and the *offline* ones. In the former, each report is processed and scheduled upon its arrival, while in the latter the OLT gathers all reports that have arrived within a maximum time duration (*polling cycle* - typically in the range of few ms, thought of as the *scheduling window* in ACCORDANCE). If the relevant timer expires, reports that have not arrived will be scheduled in the next cycle, while if all reports are collected the scheduling process proceeds to the next step. The main benefit of the offline case is that it facilitates implementation due to the reduced frequency of execution of the DBA process. However, the main drawback associated with offline report handling has to do with the extra "Report-to-Schedule" delay not present in the online case and this is the reason for employing only the online case in this work.

Step (b) is relevant only in the offline case, and is related to applying some kind of prioritization among ONUs. In other words after several, or all, reports have been collected, the OLT may choose to rearrange the order of serving the respective ONUs in a non-FIFO manner. The criteria for this rearrangement may, for example, be affected by different SLAs among ONUs.

Finally, step (c) involves the selection of the upstream rectangle where the grant for a specific report will be placed. Schemes defining this selection can obviously be combined with any of the options in steps (a) and (b). Grant scheduling schemes are further subdivided [11] in *detaining/non-detaining* (in the latter case, each grant is scheduled as early as possible while in the former it can be delayed to some extent [15]) and *horizon-based/void-filling* ones (depending on whether gaps between upstream reservations are usable for future ones or only horizon are considered for the scheduling decision). Given the heavy processing for keeping track and searching among possible voids (reported in [11] for WDM/TDMA EPONs, but further aggravated in the OFDMA-PON case due to the arbitrary dimensions of rectangles which can fit in between reservations), as well as the difficulties associated with determining the optimal detaining parameters, in this Section only *non-detaining horizon-based* schemes will be considered.

Table 2: Basic notation used.

Symbol	Description	Unit
N	Number of ONUs	–
M	Total number of upstream subcarriers	–
M_k	Maximum number of upstream subcarriers for ONU_k	–
s_i	The i^{th} upstream subcarrier	–
C	Total upstream capacity	$bits/s$
C_i	Capacity of s_i	$bits/s$
C_k	Upstream interface capacity of ONU_k	$bits/s$
S_i^j	Arrival time at the OLT of the first bit of the j^{th} scheduled upstream transmission at s_i	s
F_i^j	Arrival time at the OLT of the last bit of the j^{th} scheduled upstream transmission at s_i	s
H_i	Horizon of s_i	s
G_b	Size of the report considered during an instance of the scheduling process	$bits$
$h_k(t)$	Earliest arrival time at the OLT of the first bit of a reservation taking place at time t for ONU_k	s
R	Set of eligible rectangles during an instance of the scheduling process	–
r_l	Low subcarrier index of rectangle $r \in R$	–
r_h	High subcarrier index of rectangle $r \in R$	–
r_s	Start time of rectangle $r \in R$	s
r_f	Finish time of rectangle $r \in R$	s

5.1.3. Notation

The basic notation used is summarized in Table 2. Each ONU in the network is denoted as $ONU_k, k = 1, \ldots, N$, having a round-trip propagation time of rtt_k from the OLT. There are M upstream data subcarriers and each ONU can operate at any time only at M_k adjacent ones. The total upstream capacity is C, while the capacity of each subcarrier $s_i, i = 1, \ldots, M$ is C_i. Note that the C_i values are generally variable and depend on the exact modulation format employed *per subcarrier* as will be explained in Section 6.2. Furthermore, S_i^j and F_i^j are the arrival times at the OLT of the first and last bit of the j_{th} scheduled upstream transmission at s_i. The H_i (*horizon*) of s_i is defined as:

$$H_i = \max_j F_i^j \tag{8}$$

For any report that arrived at the OLT at time t, reporting G_B Bytes ($= G_b$ bits), the scheduling algorithm has to create the set R of eligible rectangles. Note that no rectangle can start before $h_k(t) = t + rtt_k$. Each rectangle $r \in R$ is uniquely defined by the 4-value set (r_s, r_f, r_l, r_h), whereby (r_s, r_f) are its start and finish times and (r_h, r_l) its low and high subcarrier indices respectively.

The following eligibility constraints hold for all $r \in R$:

$$r_s = \max\left[h_k(t), \max_{r_l \le i \le r_h} H_i\right] \tag{9}$$

$$r_h - r_l + 1 \le M_k \tag{10}$$

$$r_f - r_s = \frac{G_b}{\sum_{i=r_l}^{r_h} C_i} \tag{11}$$

$$C_k \ge \sum_{i=r_l}^{r_h} C_i \tag{12}$$

After each reservation, the OLT should update the S_i^j and F_i^j values for $r_l \le i \le r_h$. There is apparently a large number of duration/subcarrier range combinations for each report. As an example, Figure 21 and Figure 22 portray the multiplicity of eligible rectangles only with $r_l = i$ and when $M_k = 6$ in two respective cases: (a) All horizons are $\le h_k(t)$ and (b) existing reservations (in darker gray) extend beyond $h_k(t)$, and therefore, some rectangles have to begin later.

It should be clarified that those figures do not represent the actual transmission in the subcarriers, but rather the possible ways in which transmission can be achieved. For example, it is obvious from both figures that the larger the number of subcarriers employed, the shorter the duration of the reservation. Note though that, as depicted in Figure 22, the use of fewer subcarriers does not guarantee that the reservation will end earlier. For example, the rectangle with $M_k - 1$ subcarriers ends much earlier than the one with $M_k - 1$. The reason for that is that, as explained above and indicated by eq. (8), the subcarrier horizons (affected by previous reservations) have to be also taken into account.

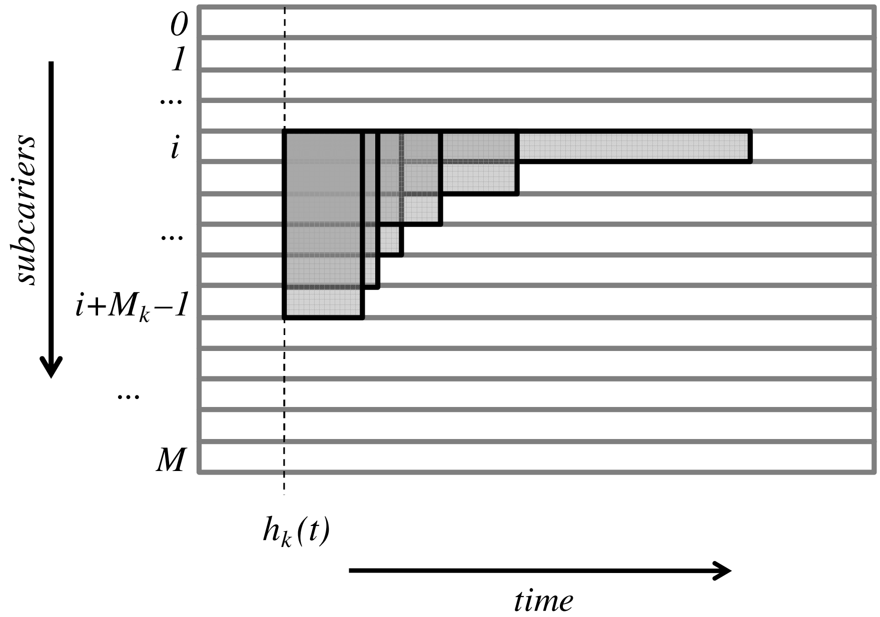

Figure 21: Candidate rectangles with $r_l = i$, in case $H_i \leq h_k(t)$ for all i.

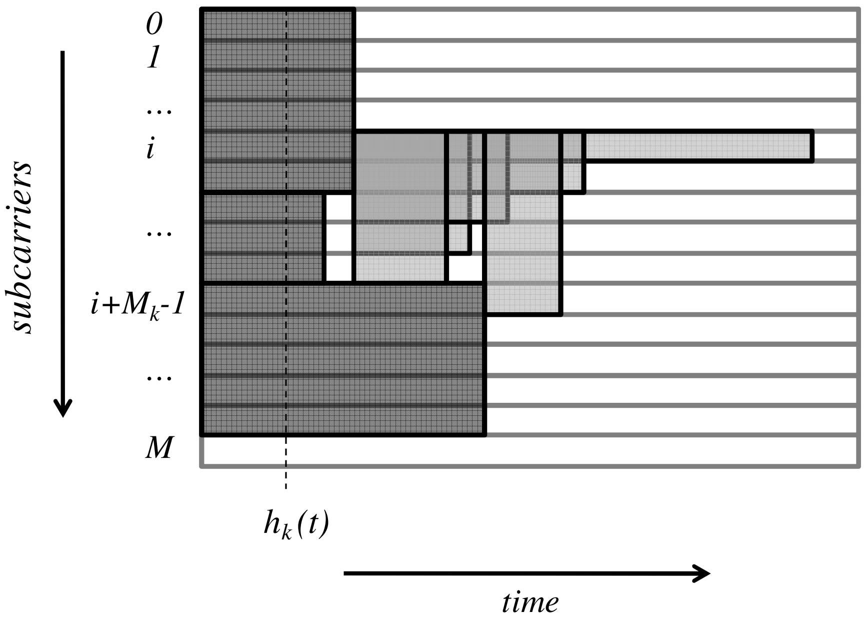

Figure 22: Candidate rectangles with $r_l = i$, in case $\exists i | H_i > h_k(t)$.

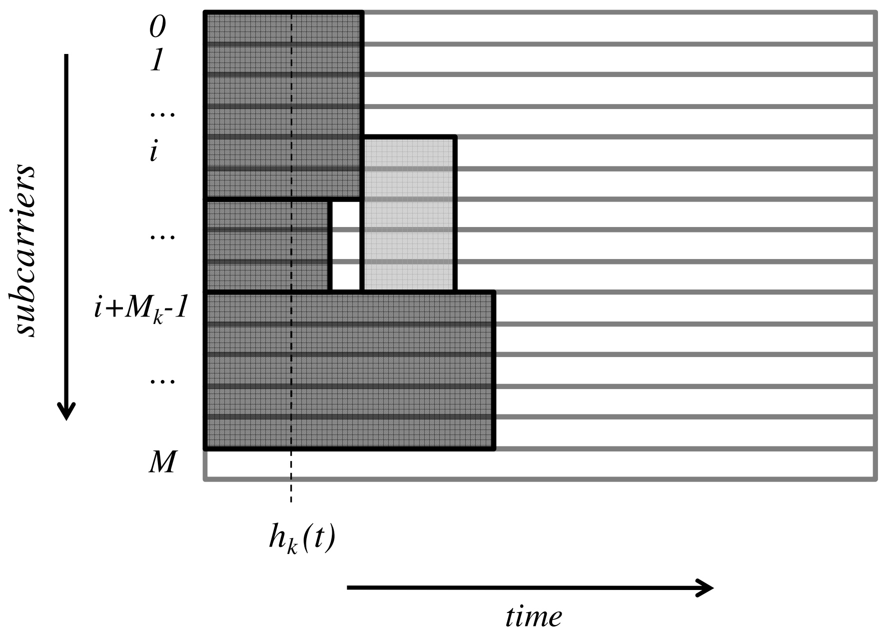

Figure 23: The rectangle selected by MAT in the example of Figure 22.

5.2. THE PROPOSED ALGORITHMS

5.2.1. *Minimum Average Time (MAT)*

Since the most important QoS performance criterion that affects almost all modern services is end-to-end frame delay, the rectangle r' chosen by the proposed *Minimum Average Time* (MAT) algorithm should possess the minimum r_{avg} value (Figure 23), where:

$$r_{avg} = \frac{r_s + r_f}{2} \tag{13}$$

In case of a r_{avg} tie among rectangles, MAT randomly selects one of them. In other words, a rectangle $r' \in R'$ is selected, whereby R' is defined as:

$$R' := arg \min_{r \in R} r_{avg} \tag{14}$$

Note that from eq. (9) and (11), r_{avg} can be written as follows:

$$r_{avg} = \max\left[h_k(t), \max_{r_l \le i \le r_h} H_i\right] + \frac{G_b}{2\sum_{i=r_l}^{r_h} C_i} \tag{15}$$

It can be seen from eq. (15) that two parameters influence the choice of the best rectangle: The maximum horizon in a set of subcarriers and their total capacity. Note that by selecting a higher amount of subcarriers it is more probable that the term $\max_{r_l \le i \le r_h} H_i$ is increased, but at the same time the higher collective capacity decreases the second term in eq. (15). Notice also how the impact of higher capacity becomes more crucial as load raises due to the increased G_b values. As a result, it is expected that the number of subcarriers selected by MAT will increase with load [although the ONU interface capacity may be a limiting factor - see eq. (12)].

5.2.2. Minimum Void Left (MVL)

Subcarrier utilization in MAT can be improved by adding a secondary criterion, *Minimum Void Left* - MVL, which is the minimization of the sum of voids from existing horizons, r_{vs}:

$$r_{vs} = \sum_{i=r_l}^{r_h} (r_s - H_i) \tag{16}$$

Therefore, MVL randomly selects a rectangle $'' \in R''$, whereby R'' is defined as follows:

$$R'' := arg \min_{r \in R\prime} r_{vs} \tag{17}$$

What MAT-MVL aims at is to minimize the effect of excessive *scheduling void* creation before each reservation, which has been shown to degrade significantly the performance of online scheduling in multi-channel EPONs [11].

The downside of MAT-MVL though is that the sum of voids needs to be calculated *per rectangle*, thus increasing algorithm complexity. Additionally, as will be described below, it is more difficult to reduce its complexity via the proposed pruning scheme.

5.3. COMPLEXITY ISSUES

5.3.1. Rectangle Search Space Pruning (RSSP)

From what has been discussed hitherto, algorithmic complexity emerges as a crucial issue due to the large number of possible rectangles, even in the horizon-based case. In any horizon-based algorithm, it is easy to show that:

$$|R| = \binom{M_k}{2}(2M - M_k + 1) \tag{18}$$

According to eq. (18), the complexity to scan through all of them in MAT can range from $O(M)$ for $M_k \approx 1$ up to $O(M^2)$, when $M_k \approx M$. Therefore, we propose the following effective method for *rectangle search space pruning* (RSSP).

- The basic idea behind RSSP is that when a rectangle R is found with:

$$r_s = h_k(t) \tag{19}$$

$$r_h - r_l + 1 = M_k \tag{20}$$

  Then the search process is terminated and the rectangle is selected, since it is certain that no better candidate (i.e. with smaller r_{avg}) is to be found. This is due to eq. (15). The latter indicates that if the first term is equal to $h_k(t)$ [i.e. condition (19)], then r_{avg} is only affected by the number of subcarriers (a higher number leads to a smaller r_{avg}).

- Additionally, as a result of the previous remark, we see that further speed-up can be achieved by rearranging the search order to consider first rectangles involving higher number of subcarriers. Although this is heuristic [a higher number of subcarriers typically, though not always – as indicated by eq. (15) – lead to smaller average times] it was shown to provide significant improvement in RSSP performance. Under this RSSP variant, it is obvious that condition in eq. (20) has to be modified so that, instead of M_k, the number of subcarriers considered in each iteration is used.

As a final remark, note that for RSSP to be applied to MAT-MVL, *all* rectangles satisfying conditions in eq. (19) and eq. (20) have to be found in each iteration. The reason is that it cannot be known in advance which of them is preceded by the smallest void.

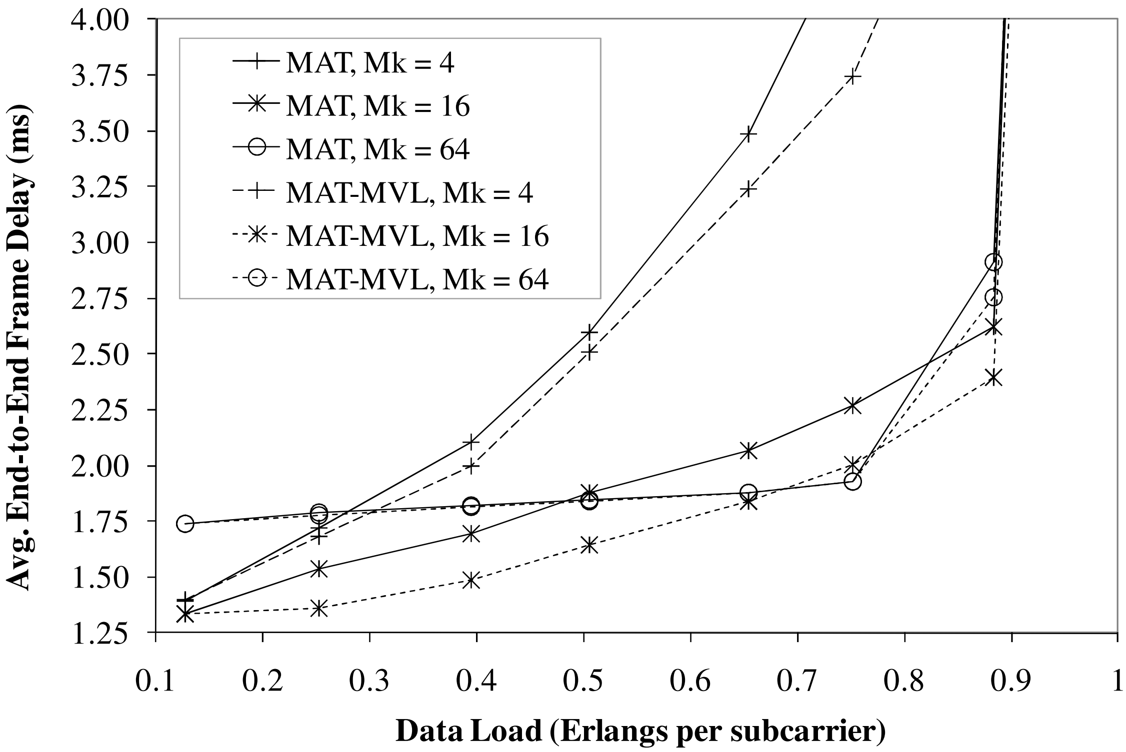

Figure 24: Comparison of MAT and MAT-MVL average end-to-end frame delay for DBPSK modulation, $N = 32$, $M = 64$, $C = 10Gbps$, OLT-ONU distances between $0 - 100km$ and various M_k values.

5.4. Performance Evaluation

5.4.1. Simulation Setup

In line with the parameters discussed above, the custom OFDMA-PON simulation model developed in OPNET Modeler comprised $N = 32$ ONUs. OLT-ONU distances were uniformly distributed between $0 - 25km$, $0 - 50km$ and $0 - 100km$ in different scenarios. The total upstream data capacity was $C = 10Gbps$ (when Differential Binary Phase Shift Keying (DBPSK) is employed), arranged in $M = 64$ subcarriers of $156.25Mbps$ each. Each ONU produced Ethernet frames (sizes uniformly distributed between 64-1518 Bytes using multiple ON-OFF sources with Pareto-distributed ON/OFF periods and a Hurst parameter $H = 0.8$. A guard time of $5\mu s$ was assumed between upstream transmissions by different ONUs. ONUs possessed 10G Ethernet interfaces ($C_k = 10Gbps$) and a buffer of 1MB each.

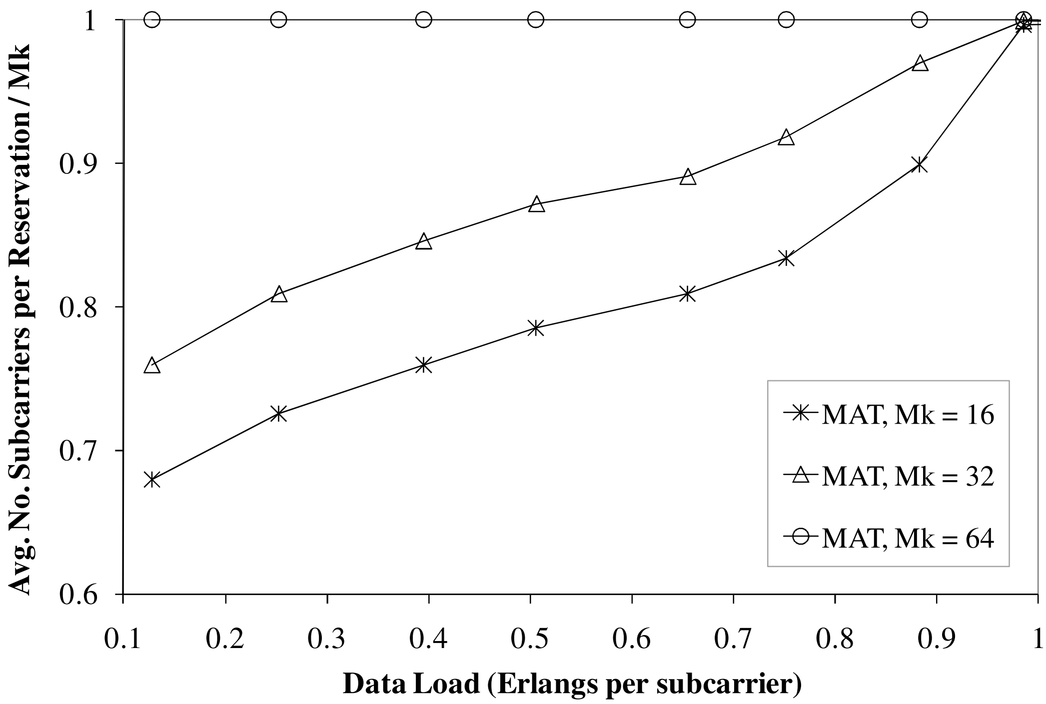

Figure 25: Average number of subcarriers selected by MAT compared to M_k for DBPSK modulation, $N = 32$, $M = 64$, $C = 10Gbps$, OLT-ONU distances between $0 - 100km$ and various M_k values.

5.4.2. Numerical Results

The first set of results compares performance of the proposed algorithms when no ASM is employed and for OLT-ONU distances ranging from $0 - 100km$. More specifically, Figure 24 depicts average MAT and MAT-MVL delay for different M_k values. It can be observed that for low-moderate load, performance in all cases is optimized for $M_k \approx 16$. The reason is that a very small M_k does not provide sufficient available bandwidth to each ONU, while too large a M_k causes far ONUs to block more horizons for near ONUs (which could otherwise be scheduled much earlier). The use of MVL rectifies this effect to some extent, especially when $M_k \approx 16$, but at the cost of increased complexity. As load increases, the use of more subcarriers tends to slightly improve performance due to the possibility of forming faster transmission pipes, however again the improvement does not justify the considerably higher complexity in that case. Therefore, from both a QoS and algorithmic complexity point of view, the maximum number of subcarriers allocated to each ONU should be kept limited.

Figure 25 reveals the flexible nature of the proposed DBA scheme and provides insight to MAT operation by depicting the average number of subcarriers selected per

ONU reservation. In general, this number approaches M_k for increasing load, which can be explained as follows (see also Section 5.2.1). As load increases, so do the report sizes, making it more probable that a rectangle has a lower r_{avg} due to its higher subcarrier count rather than its earlier start time. Note also that when $M_k = 64$ the operation is essentially TDMA (it is always beneficial from a delay point of view to use all the available subcarriers).

Figure 26 shows the reduction of the candidate rectangles searched compared with the total amount of eligible rectangles, when augmenting MAT with RSSP. It is impressive that for moderate load the search space can be reduced up to 80% and 30% for $M_k = 4$ and $M_k = 16$ respectively, facilitating significantly implementation of the algorithm.

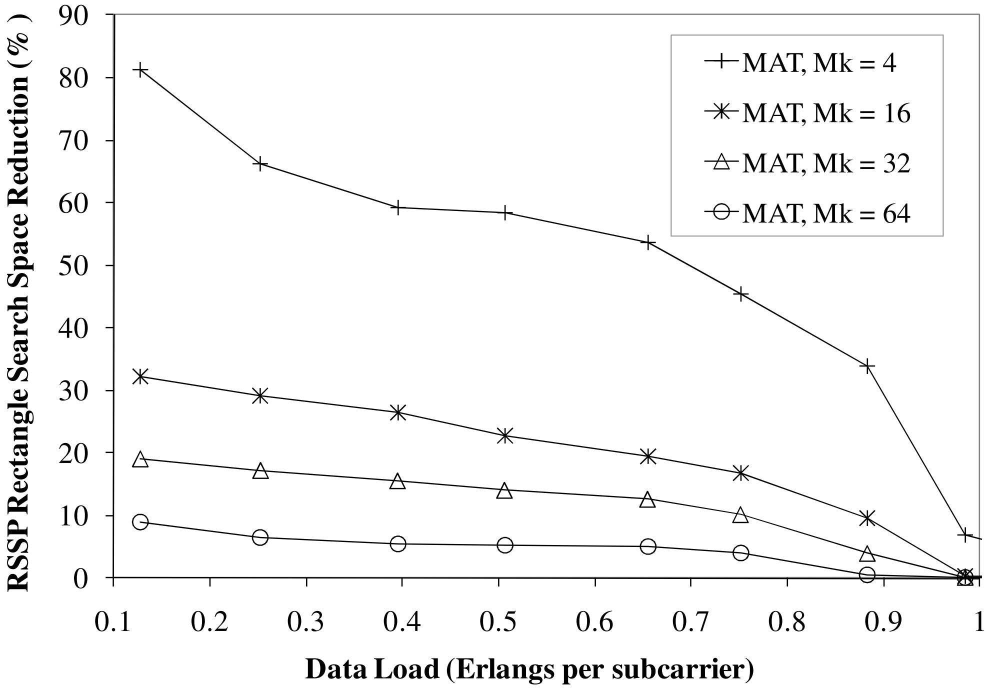

Figure 26: Reduction of the MAT rectangle search space offered by RSSP (as a percentage of the total amount of eligible rectangles) for DBPSK modulation, $N = 32$, $M = 64$, $C = 10Gbps$, OLT-ONU distances between $0 - 100km$ and various M_k values.

Coming back to the issue of optimal selection of M_k, Figure 27 depicts the M_k values offering the best average delay at each network load for a network with OLT-ONU distances between $0 - 50km$. It is clear from the figure that the optimal M_k depends on the load, ranging from 8 to 64.

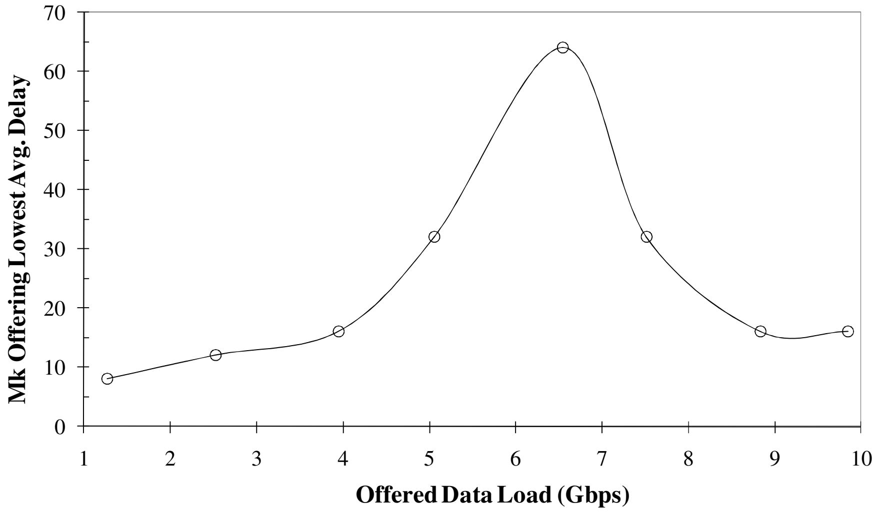

Figure 27: The M_k values offering the lowest average delay at each load for DBPSK modulation, $N = 32$, $M = 64$, $C = 10Gbps$ and OLT-ONU distances between $0 - 100km$.

However, Figure 27 should be evaluated in conjunction with Figure 28**Error! Reference source not found.**. The latter shows how close is the delay offered by each M_k to the lowest possible average delay at each offered load region. It is evident here that, although at different loads either smaller or larger M_k values are optimal, the M_k that can offer the best performance throughout the whole load range is around 16, thus providing a very useful rule of thumb for selecting this scheduling parameter. Moreover, note that processing of a reduced number of subcarriers at the user side is also in line with the requirement for ONU equipment that is as cost-effective as possible.

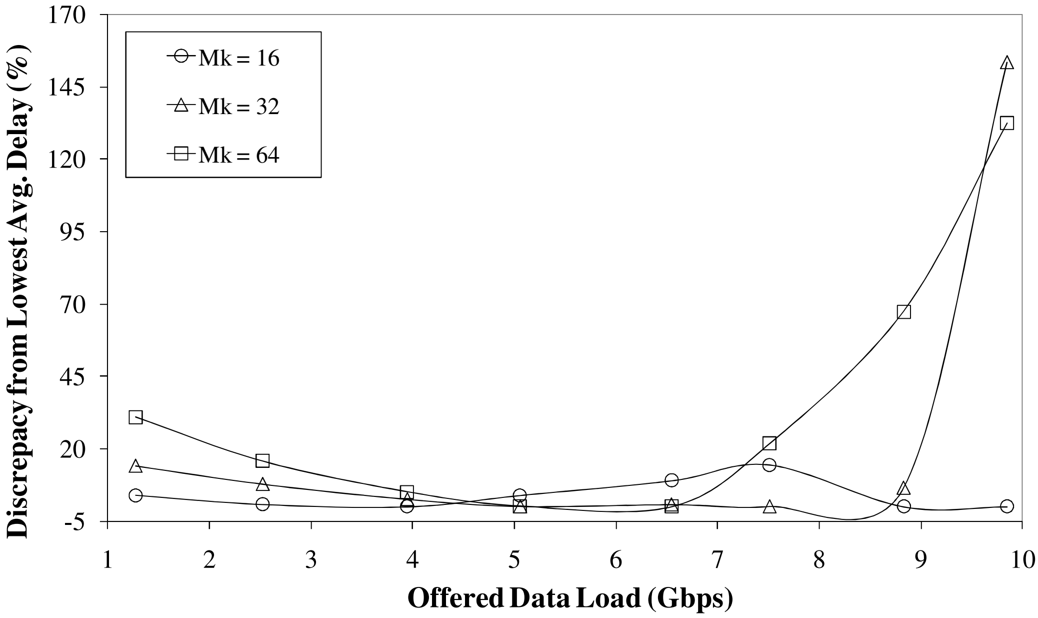

Figure 28: Discrepancy of the average delay offered by various M_k values from the lowest average delay at each load for DBPSK modulation, $N = 32$, $M = 64$, $C = 10Gbps$ and OLT-ONU distances between $0 - 100km$.

As a final note, it should be stressed that all conclusions extracted here regarding the optimal M_k can be applied for any M, with the values scaled accordingly. This was also verified by further simulation experiments performed. The results presented in Figure 29 show that for $M = 256$ the performance of MAT is absolutely comparable to what was shown in Figure 24, for the same M_k/M ratios.

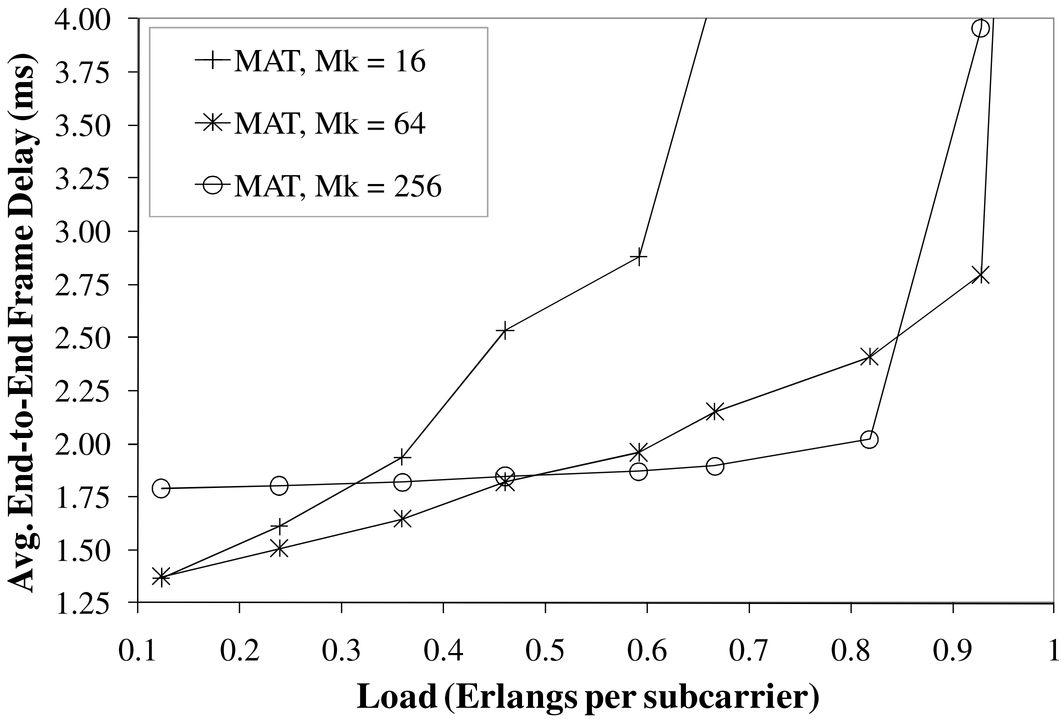

Figure 29: MAT average end-to-end frame delay for DBPSK modulation, $\mathbf{N = 32}$, $\mathbf{M = 256}$, $\mathbf{C = 10Gbps}$, OLT-ONU distances between $\mathbf{0 - 100km}$ and various $\mathbf{M_k}$ values.

6. Cross-Layer Scheduling Employing Adaptive Subcarrier Modulation

6.1. Introduction

As described in D4.2, in ACCORDANCE an ASM scheme per ONU is proposed. We assume that modulation takes place using the m-QAM format, with varying modulation levels m. Since the number of bits transmitted per Orthogonal Frequency Division Multiplexing (OFDM) symbol is given by $\log_2 m$, it is obvious that bitrate is dependent on the exact choice of modulation format. The proposed ASM scheme involves using a different modulation format per ONU, decided upon registration and based on a per-ONU monitoring by transmission performance (large constellation maps lead to increased BER when the overall signal power remains the same). ASM naturally affects significantly the MAC process in ACCORDANCE, since different bitrates have to be taken into account per subcarrier during the proposed DBA algorithms.

In this section we jointly study the operation of the MAC algorithms defined in Chapter 5 along with the ASM concept, with the goal being to increase aggregate network capacity (hence improve the offered QoS for the same offered load and vice versa) with acceptable physical layer performance degradation. Note that it is the first time to our knowledge that such a scheme is incorporated with the PON MAC DBA process to leverage on cross-layer optimization benefits.

6.2. Physical Layer Operation

Throughout the rest of section, Intensity-Modulation and Direction-Detection (IM-DD) Optical OFDM ([16], [17], [18], [19]) is assumed for the physical layer, although in essence any technological option from the ones defined within ACCORDANCE (see Deliverable D2.2) could have been chosen. Below we briefly recapitulate the basic physical layer procedures associated such an IM-DD setup:

At the transmitter (Tx), a Serial-to-Parallel converter (S/P) splits the incoming data sequence into a large set of new ones which will form the transmitted subcarriers. Then, the produced binary data sequences are encoded to serial complex numbers using the signal modulation format assigned to the specific ONU. As mentioned above, in ACCORDANCE we consider the same modulation format across all subcarriers assigned to each ONU in order to keep ONU complexity at low levels. The QAM formats considered range from DBPSK,$m = 2$, Differential Quadrature Phase Shift Keying (DQPSK, $m = 4$) and 8-QAM, up to 256-QAM. Parallel adaptive DBPSK/DQPSK/m-QAM modulators/demodulators are required to enable operation at any possible modulation format (the same ONU device should be able to be used by any customer in the network). Note also that the OLT-ONU negotiations required to enable ASM are handled by the MAC layer, as has been explained in detail in D4.2.

Following the modulation stage, an Inverse Fast Fourier Transform (IFFT) is applied to the set of subcarriers in order to generate parallel real-valued OFDM symbols. For the generation of this real-valued OFDM signal waveform, the OFDM symbols created have the original data in the positive frequency bins and the complex conjugate of the data in the negative frequency bins. In addition, no power is contained in the first subcarrier close to the signal baseband. Such a modification doubles up the number of subcarriers within an OFDM symbol. Moreover, a Cyclic Prefix (CP) in front of each symbol is added to combat link dispersion [17] (leading though to increased bandwidth overhead – which is also taken into account in the performance evaluation section). The symbols are then serialized by a Parallel-to-Serial converter (P/S) to form a long digital signal sequence, to which signal clipping is applied for the purpose of limiting overall signal power within a predetermined range. Finally, a Digital-to-Analogue Converter (DAC) is used to convert the digital data sequence into an analogue signal waveform, which is ready to drive directly a Distributed Feedback laser (DFB) that will produce an optical OFDM signal waveform at the required carrier frequency.

At the Rx side, the optical signal emerging from the link is detected by a square-law photo-detector. After passing through a Low Band-Pass Filter (LPF) and an Analogue-to-Digital Converter (ADC), the electrical signal is decoded into the original sequence by the Rx, which is in essence the inverse of the Tx described above.

Following the discussion above, the aggregate upstream capacity C can be expressed as seen next in eq. (21). C_i denotes the signal bit rate transmitted by the i^{th} data subcarrier, $\log_2 m_i$ is the total number of binary bits conveyed by the i^{th} subcarrier within one symbol period, M is the total number of data-carrying upstream subcarriers in the positive frequency bins, S is the aggregate sampling rate of the OLT ADC and P is the used CP (expressed as a ratio of the symbol duration [19]).

$$C = \sum_{i=1}^{M} C_i = \frac{S \sum_{i=1}^{M} \log_2 m_i}{2M(1+P)} \tag{21}$$

Note that for simplicity (and without loss of generality), in eq. (21) we have not taken into account additional subcarriers required for other purposes as described in 5.1.1 (and which are in any case expected to be much fewer than the data subcarriers).

6.3. Effects of ASM on MAC Operation

The procedures required from the ACCORDANCE MAC layer in order to support ASM have been described in detail in Deliverable D4.2 [2].

The ONUs should first of all inform the OLT regarding their supported modulation formats during registration. Additionally, the MAC should take care of control message exchanges that allow for dynamically modifying the modulation format used by each ONU. The OLT must perform a series of control message exchanges per ONU testing a different modulation format each time. For example, it could begin by monitoring the BER for the lowest possible number of m-QAM levels ($m = 2$ - corresponding to DBPSK modulation) and repeat the process for increasing m until a predefined threshold BER_{th} is exceeded. In addition there is a special Physical Layer Operations and Maintenance (PLOAM) messaging (as described in Section 5.2.4 of D4.2) from the OLT to the ONU to inform the latter about the selected m-QAM format.

Remarks on the use of ASM alongside ACCORDANCE are provided below:

- When ASM is employed, different rectangles are produced for each ONU per (r_l, r_h) pair. This is due to the fact that according to eq. (21), C_i in eq. (11) and (12) depends on the modulation format m_i of the ONU to which s_i is temporarily assigned.
- No significant benefit is expected by altering the modulation format of any ONU during normal network operation (i.e. link transmission properties cannot change much so as to justify lowering down the QAM levels).
- In addition, ASM could potentially be used as a means of policing based on individual ONU SLAs, i.e. a sub-optimal format could be employed if the user is subscribed to a lower rate. Nevertheless, since such policing can also be

achieved via the scheduling process, the only plausible reason for doing so would be to achieve better transmission performance.

- ONUs located closer to the OLT are naturally expected to be able to choose among a higher number of possible modulation schemes. Therefore short-term unfairness issues could be raised; however as will be shown in the performance evaluation section, they are alleviated in the end since ASM ultimately leads to improved average performance for all ONUs. In fact, DBA gains in flexibility when the optimal format is employed per ONU. The increased maximum capacity of some ONUs (it must be stressed again that this is not at the cost of the other ONUs' capacity) can only benefit the rest, since it produces savings in the scheduling space occupied – according to eq. (10), either fewer subcarriers can be chosen or the duration of reservations is shortened.

Table 3: Physical Layer Simulation Results.

Modulation Format	BER_{th}	Maximum Distance (km)
DBPSK	10^{-3}	53
DBPSK	10^{-5}	52
DBPSK	10^{-7}	46
DBPSK	10^{-9}	42
16-QAM	10^{-3}	28
16-QAM	10^{-5}	27
16-QAM	10^{-7}	25
16-QAM	10^{-9}	24
256-QAM	10^{-3}	2
256-QAM	10^{-5}	1.5
256-QAM	10^{-7}	0.8
256-QAM	10^{-9}	0.4

6.4. Performance Evaluation

6.4.1. Simulation Setup

For the evaluation of the proposed schemes a hybrid computer simulation setup was developed. Physical layer performance for various modulation formats was simulated using Matlab. Accordingly, those results were used as input for modulation format selection during the ONU registration process of a MAC layer simulation model developed in OPNET Modeler. Using the latter, the performance of the scheduling schemes presented in Section 5 was compared under various settings (including ASM). Below we describe the parameters used for each part of the simulation setup and then we present and discuss the results obtained.

Transmission was performed using Standard Single-Mode Fiber (SSMF), while ideal splitting losses were considered (i.e. $15.05dB$ for 1:32 splitting ratio). The OFDM scheme used was IM-DD, as described in Section 6.2. DFB-DML lasers were used at the ONU transmitter, with a bias current of $30mA$, a peak-to-Peak drive current of $15mA$ (optimum parameters) and launched optical power equal to $5dbm$. The clipping ratio was $13dB$ and the number of quantization bits was 7. The CP was 12.5% of the OFDM symbol duration, while the total number of data subcarriers was 64 (though the number of *transmitted* subcarriers was 128 due to the IM-DD configuration). The modulation formats considered ranged from DBPSK up to 256-QAM and, for each, the maximum achievable distance for $BER_{th} = 10^{-3}, 10^{-5}, 10^{-7}, 10^{-9}$ was calculated. Table 3 includes indicative results extracted for DBPSK, 16-QAM and 256-QAM.

6.4.2. Numerical Results

As was the case in Section 5 as well, the main performance metric of interest was the average end-to-end frame delay. However, to provide some additional insight in the operation of the combined MAT-ASM scheme, in Figure 30 we show the number of assigned subcarriers per reservation in the case of fixed DBPSK modulation and when ASM is applied with varying BER thresholds. It is clear that, as expected, the number of assigned subcarriers per reservation is reduced significantly in ASM due to their increased average capacity. In particular, the amount of subcarriers used by ASM can be up to $2/3$ of the DBPSK case. This implies that by employing ASM it can be possible to relax ONU requirements in terms of the maximum number of subcarriers supported.

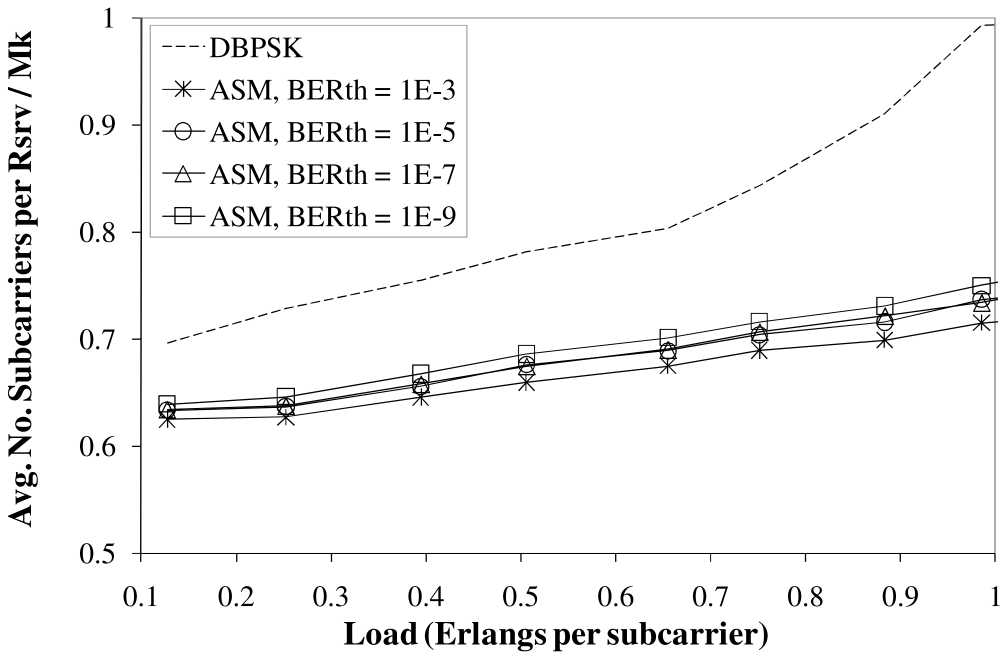

Figure 30: Average number of subcarriers selected by MAT in the case of DBPSK modulation and ASM with various BER_{th} values, $N = 32$, $M = 64$, $M_k = 16$, $C = 10Gbps$ and OLT-ONU distances between $0 - 50km$.

However, the most interesting results regarding the benefits of ASM are provided in Figure 31 and Figure 32. Figure 31 depicts average end-to-end delay for various BER thresholds as opposed to the case when simple DBPSK modulation is used for all subcarriers, again for OLT-ONU distances between $0 - 50km$. One general observation is that ASM greatly boosts delay performance in all cases (even with $BER_{th} = 10^{-9}$, but especially for higher BER_{th} values. In particular, for $BER_{th} = 10^{-3}$ the offered load can reach up to almost $13Gbps$ while keeping average delay at reasonable levels (i.e. $5ms$), as opposed to around $8Gbps$ in the DBPSK case. Of course, since this comes at the cost of increased BER, it would in turn translate to increased packet loss in a real system (packet loss, along with delay, constitutes the other critical QoS metric). However, given that typically Forward Error Correction (FEC) is expected to be employed (e.g. it is already specified as a prerequisite in [9] - though at the cost of extra overhead), then even the use of a high BER_{th} has the potential to combine reasonable packet loss with superior delay performance.

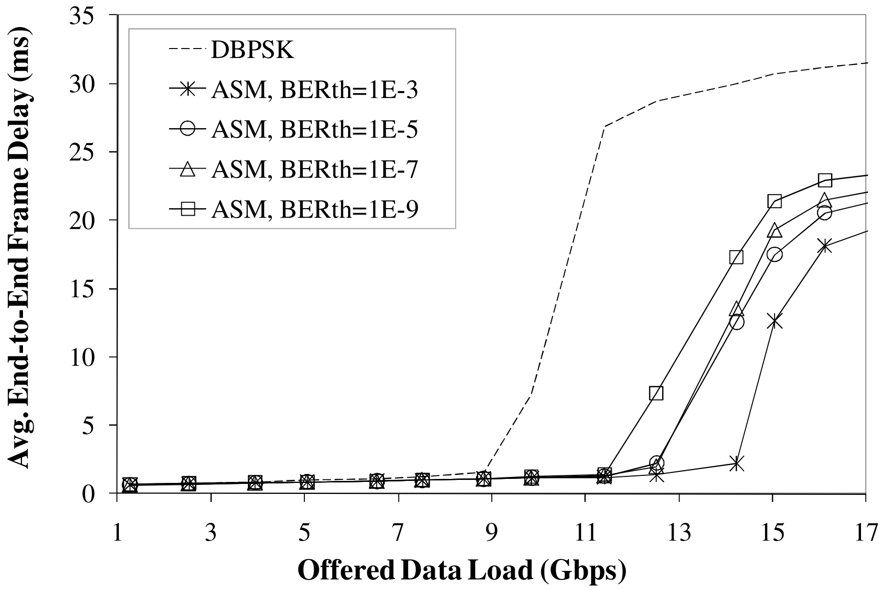

Figure 31: MAT average end-to-end frame delay comparison between DBPSK modulation and ASM with various BER_{th} values, $N = 32$, $M = 64$, $M_k = 16$, $C = 10Gbps$ and OLT-ONU distances between $0 - 50km$.

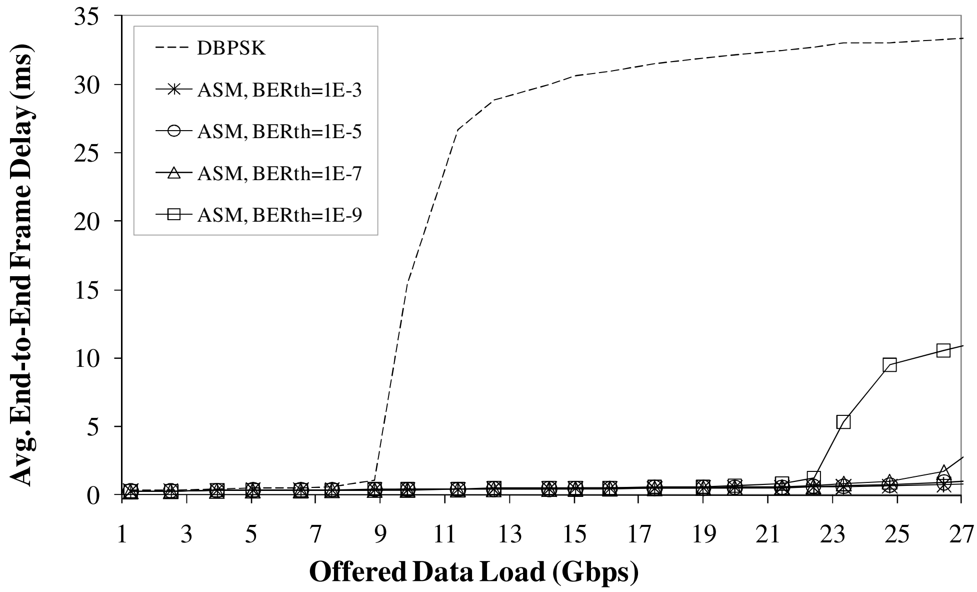

Figure 32: MAT average end-to-end frame delay comparison between DBPSK modulation and ASM with various BER_{th} values, $N = 32$, $M = 64$, $M_k = 16$, $C = 10Gbps$ and OLT-ONU distances between $0 - 25km$.

Finally, Figure 32 shows ASM performance in a shorter-reach network (OLT-ONU distances between $0 - 25$km). It is clear that even more significant performance benefits can be obtained in that case, since more ONUs have now the opportunity to select higher-order modulation formats. More specifically, the offered load that can be handled by the network, while keeping average delay at the same levels, is almost doubled, compared to the $0 - 50$km case.

7. Sequential Dynamic Subcarrier Allocation for Long Reach Networks

7.1. Long Reach ACCORDANCE

By reason of the imposed long propagation delays of the extended network reach, the direct implementation of the SDSCA algorithm using ONU reports for the allocation of bandwidth is expected to exhibit low channel utilisation and excessive packet delay. This is the consequence of the fact that for service level integration, the OLT has to establish the bandwidth requirements of all ONUs, before it imparts the upstream bandwidth maps to notify ONUs about their allocated bandwidth. In view of a 100 km long-reach ACCORDANCE architecture, the upstream channel will remain idle between two polling cycles for prolonged periods, compared for example to standard 20 km architectures. This is due to an up to 0.5 ms increase in packet propagation time, from 0.1 ms in the 20 km scenario, as illustrated in Figure 33.

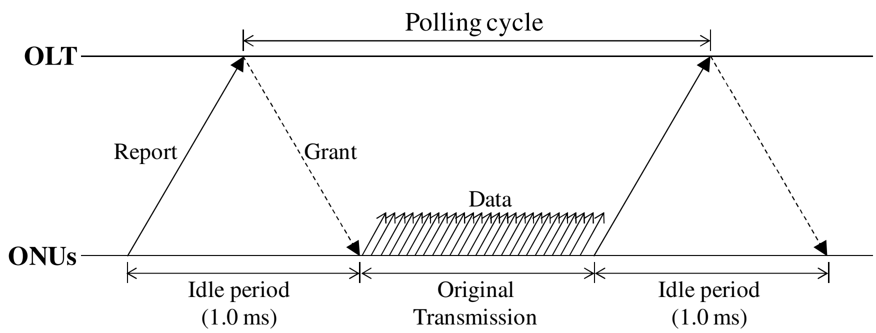

Figure 33: Idle periods in 100 km SDSCA with reporting.

To overcome these limitations the idle period in each polling cycle in Figure 33, should naturally be utilized for data transmission, increasing the effective transmission bandwidth. This requirement can be achieved by the application of the SDSCA algorithm, employing monitoring rather than reporting, for bandwidth allocation. The reason being that monitoring avoids the formation of idle periods, even in long-reach network scenarios, since the OLT does not wait for report messages from ONUs before it departs bandwidth. The monitoring SDSCA bandwidth distribution is shown in Figure 34.

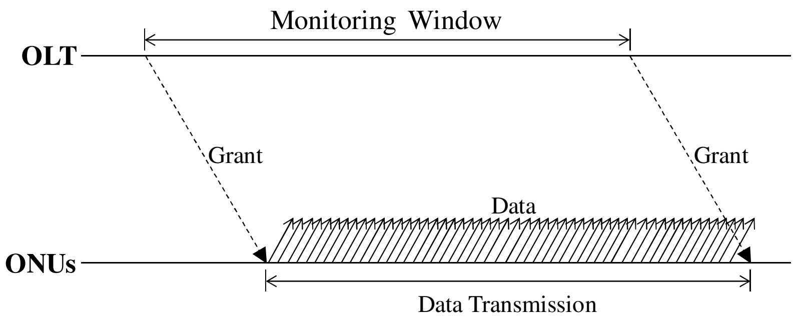

Figure 34: **SDSCA with monitoring in 100 km ACCORDANCE**

7.2. Long-reach SDSCA Algorithm Performance Evaluation

Table 4 presents the simulation parameters required for data link layer modeling, OPNET implementation and performance evaluation of the long-reach, SDSCA algorithm. CoS differentiation and network traffic generation are also specified. The current simulation design exhibits a 100 km OFDMA-PON composed of one OLT and 64, 128 and 256 ONUs. It should be emphasized that the value of the ONU offered load is different in each case according to the number of ONUs. A load of 1.0 defines 625 Mbps, 312.5 Mbps and 156.25 Mbps in the case of 64, 128 and 256 ONUs respectively.

Table 4: SDSCA simulation parameters for long-reach networks.

Parameters	Description	
Total network capacity	40 Gbps	
Number of subcarriers	256	
Data rate per subcarriers	156.25 Mbps (40 Gbps / 256)	
Number of time slots per subcarrier	4	
Data rate per time slot	39.06 Mbps (40 Gbps / 256 / 4)	
Number of ONUs	64	
	$SLA_0 : SLA_1 : SLA_2 = 4 : 20 : 40$	
Guaranteed Data Rate per SLA (SLA_TS)	SLA_0	742.14 Mbps
	SLA_1	664.02 Mbps
	SLA_2	585.9 Mbps
Number of ONUs	128	
	$SLA_0 : SLA_1 : SLA_2 = 8 : 40 : 80$	

Guaranteed Data Rate per SLA (SLA_TS)	SLA_0	507.78 Mbps
	SLA_1	351.54 Mbps
	SLA_2	273.42 Mbps
Number of ONUs	256	
	$SLA_0 : SLA_1 : SLA_2 = 16 : 80 : 160$	
Guaranteed Data Rate per SLA (SLA_TS)	SLA_0	312.5 Mbps
	SLA_1	195.3 Mbps
	SLA_2	117.18 Mbps
Distance between OLT and ONU	100 km	
Monitoring window time and polling cycle	2.0 ms	
Grant processing delay	5 µs	
Propagation delay	5 µs/km	
ONU offered load 1.0	625 Mbps (40 Gbps / 64) for 64 ONUs	
	312 Mbps (40 Gbps / 128) for 128 ONUs	
	156 Mbps (40 Gbps / 256) for 256 ONUs	
Network offered load 1.0	40 Gbps	
Packet size	64 – 1518 Bytes (Uniformly generated)	
Traffic generation of CoSs	High priority CoS0: 20 %	
	Middle priority CoS1: 40 %	
	Low priority CoS2: 40 %	

Figure 35 represents the network throughput recorded, following the simulation of both the monitoring SDSCA and reporting SDSCA algorithms as a function of the network offered load. A load of 1.0 corresponds to a data rate of 40 Gbps with 64 ONUs at this instant. The saturated throughputs are 96.5 % (38.6 Gbps/40 Gbps) and 49.5% (19.8 Gbps/40 Gbps) for the monitoring SDSCA and reporting SDSCA respectively, demonstrating directly the limitation of the reporting SDSCA algorithm in coping with longer distances. The reason for the low throughput of reporting SDSCA is that ONUs use only 50% of the polling cycle due to the propagation delay of Grant/Report messages. The difference in network throughout by 51% is purely due to the monitoring SDSCA utilizing the transmission cycle much more effectively.

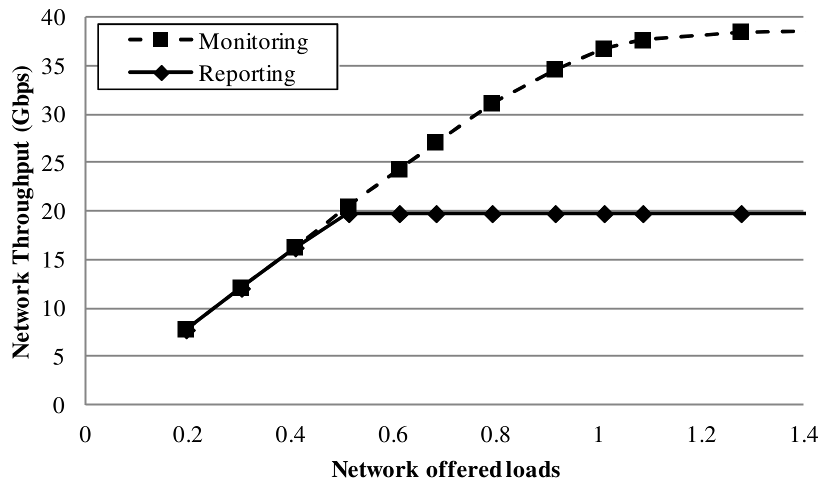

Figure 35: Comparison of network throughput with 64 ONUs.

Figure 36 illustrates the end-to-end packet delay comparison between the two algorithms. The end-to-end delay of the reporting SDSCA saturates early compared to the monitoring SDSCA. For example, the saturated traffic load of SLA_2 originates after 0.4 of the network load in the former, corresponding to 250 Mbps (625 Mbps × 0.4).

In contrast, the end-to-end packet delay of the low priority SLA, SLA_2, of the monitoring SDSCA only saturates at 0.9 offered load, with the middle and high priority SLAs displaying less than 1.6 ms packet delay, even if the ONU offered load is 1.0. This is because the guaranteed bandwidths of the high and middle SLAs are greater than the ONU offered load of 1.0, corresponding to 625 Mbps, as shown in Table 4.

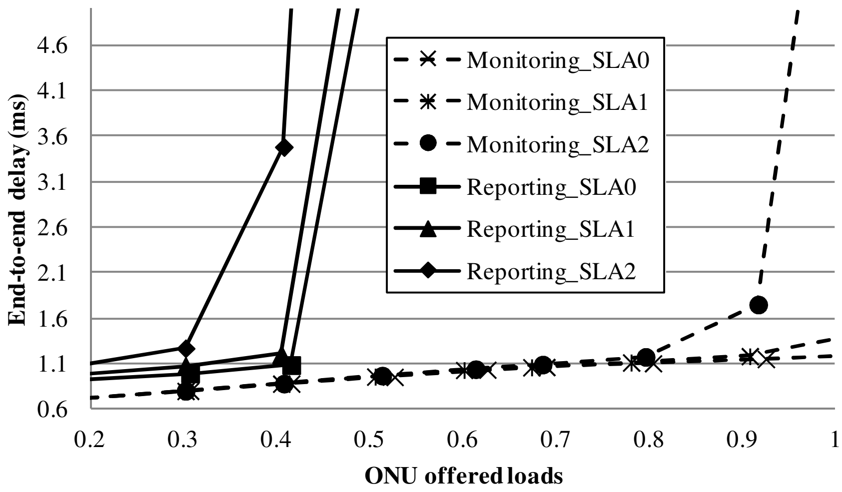

Figure 36: Comparison of end-to-end delay with 64 ONUs.

Figure 37 displays network performance in throughput in the presence of 128 ONUs. The throughput achieved with the reporting SDSCA is 49 % of the total network capacity with 46% increase recorded, as expected, in the use of the monitoring SDSCA algorithm. The capacity actual numbers achieved with 128 ONUs are lower than with 64, as well as the variation figure between the two trends.

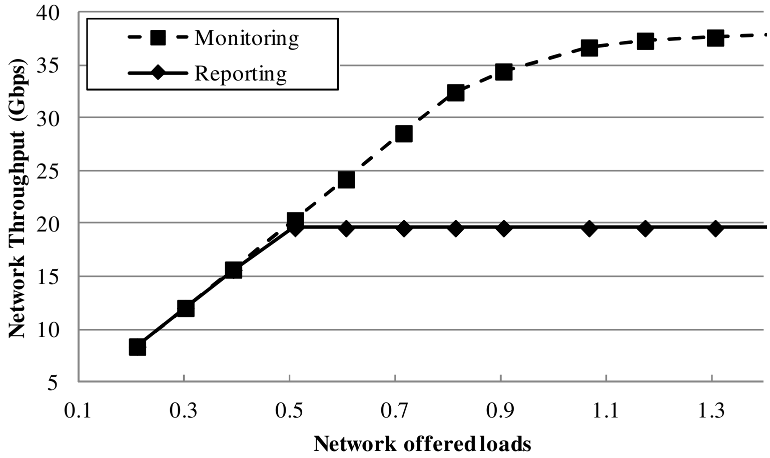

Figure 37: Comparison of network throughput with 128 ONUs.

Similarly to the 64 ONU network, Figure 38 represents the end-to-end delay results with 128 ONUs. All saturation points of the reporting SDSCA appear earlier than in the monitoring SDSCA figures, following the expected trend. For example, the saturated traffic load of reporting SDSCA SLA_2 originates at about 0.4 of the ONU offered load, corresponding to 125 Mbps (312.5 Mbps × 0.4), even if the guaranteed data rate of SLA_2 was defined at 273 Mbps, as shown in Table 4. This is the consequence of the limited use of the allocated bandwidth. In contrast, the saturated traffic load of the monitoring SDSCA SLA_2 ONUs, appears just after 0.7 of the ONU offered load, corresponding to 218 Mbps (312.5 Mbps × 0.7).

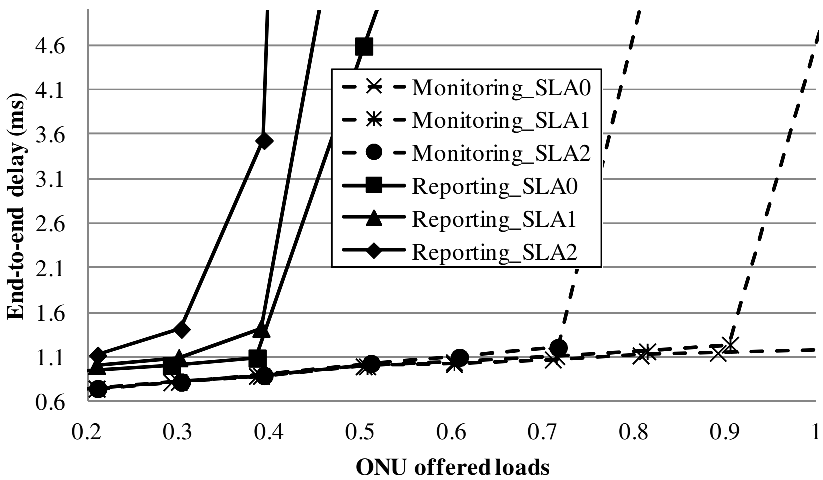

Figure 38: Comparison of end-to-end delay with 128 ONUs.

Figure 39 and Figure 40 illustrate the network throughput and packet delay for the 256-ONU network. A network load of 1.0 corresponds to a data rate of 40 Gbps (total upstream data capacity). The monitoring SDSCA algorithm manages to utilize 93.75 % of the total capacity. In the packet delay graph, SLA_2 ONUs, using the reporting SDSCA algorithm, also saturate early, displaying 62.4 Mbps (156.25 Mbps × 0.4) of potential data transfer, reduced by about 50% with respect to the specified guaranteed bandwidth. The worst case performing ONUs, in use of the monitoring algorithm, achieve 82 Mbps before delay deteriorates data transfer, down by less than 30% of their originally defined guaranteed bandwidth.

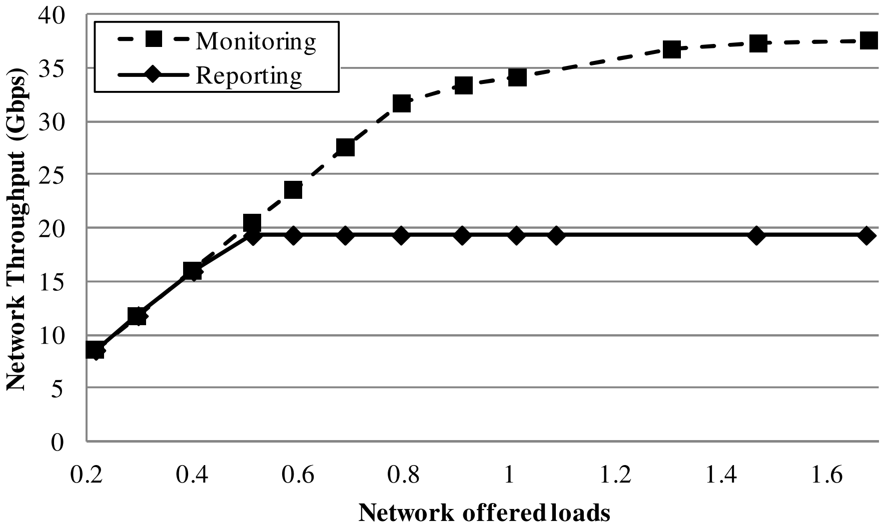

Figure 39: Comparison of network throughput between with 256 ONUs.

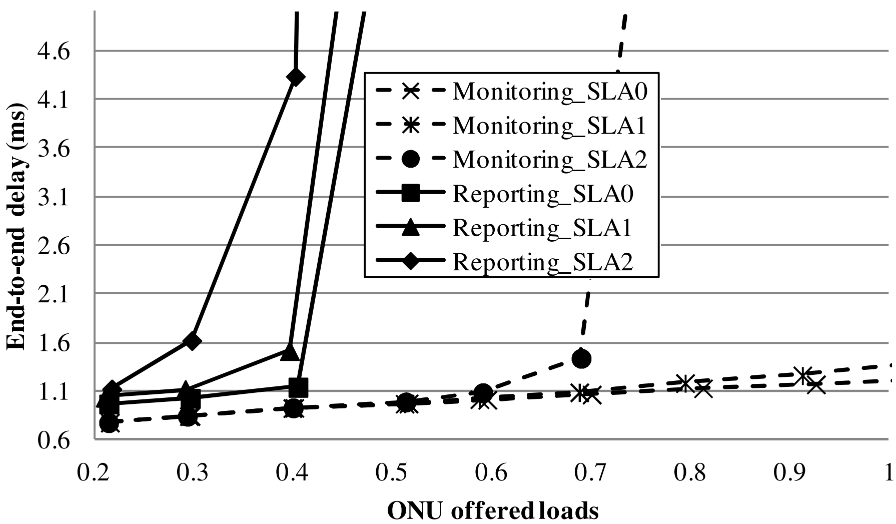

Figure 40: Comparison of end-to-end delay with 256 ONUs.

Conclusions

D4.3 concentrates on the bandwidth assignment schedule and performance evaluation of new algorithm designs, exhibiting service level agreement and CoS differentiation over 20, 40 and 100 km reach, and 32, 26 and 256-split OFDMA-PONs, with the ACCORDANCE network representing the underlying infrastructure. Having established the requirement for upgrading the available or developing standards to allow OFDMA operation and following the specifications provided in D4.2 in protocol functionalities, frame formats and control fields by means of extending the 10GEPON and XGPON, both EPON and GPON-based algorithms have been investigated. In particular, a DSCA algorithm was initially explored to allow bandwidth distribution only in the frequency domain, providing simpler MAC protocols and higher throughput utilization. By integrating the advantages of TDMA and OFDMA, hybrid OFDMA/TDMA algorithms have also been proposed to provide increased granularity. To that effect, one or more dedicated subcarriers can be assigned to an ONU to guarantee its minimum bandwidth and then, dynamically share any unused subcarriers between ONUs with bandwidth requirements higher than the minimum guaranteed. In addition, the hybrid scheme is supported by two mechanisms to allow the OLT to distribute bandwidth to ONUs, exhibiting monitoring as well as reporting. To that extent the GPON-based SDSCA and the EPON-based R-DSCA algorithms have been reported.

Network performance investigations, with 32 ONUs and over 40 km reach, of the monitoring based SDSCA versus the reporting based SDSCA algorithm have displayed significant 1.1 Gbps increase in channel throughput, with an improvement in packet delay and packet loss rate to allow high network throughput over extended network loads. End-to-end packet delay for SLA_1 ONUs at accustomed 90% ONU load has displayed 7 times reduction under the monitoring based SDSCA compared to the reporting based SDSCA algorithm. It is also demonstrated that by considering CoS in the ONUs, low delay transmission is achieved for CoS_0 time-sensitive traffic, demonstrating the efficiency of the algorithm in supporting QoS for VoD and/or UHDTV services, under any network offered load condition. Additionally, 3 and 10 times reduction in packet delay is achieved for CoS_1 and CoS_2 traffic, respectively, signifying the advancements offered by the monitoring based SDSCA in efficiently and flexibly arranging the network capacity to support increased volume multimedia services. To present an alternative evaluation merit of the monitoring based SDSCA performance, the application of the developed algorithms over 40 km reach OFDMA-PONs has demonstrated comparable performance figures in terms of network throughput, end-to-end packet delay and packet loss rate to currently deployed reporting based protocol.

Regarding RDSCA-based scheduling, the MAT algorithm which assigns upstream bandwidth in rectangles trying to minimize the average delay of each reservation was proposed and evaluated. The MAT-MVL variant of MAT manages to slightly increase utilization and improve delay performance however at the cost of increased complexity (which is already considerable even in the case of MAT). In that respect, the proposed RSSP scheme was employed to significantly reduce the computational complexity of MAT by pruning the rectangle search space.

The combined use of MAT with ASM was shown to greatly boost delay performance (even with $BER_{th} = 10^{-9}$, but especially for higher BER_{th} values). In particular, for $BER_{th} = 10^{-3}$ the offered load can reach up to almost $13Gbps$ while keeping average delay at reasonable levels (i.e. $5ms$), as opposed to around $8Gbps$ in the DBPSK case. ASM performance in shorter-reach networks (OLT-ONU distances between $0 - 25km$) show more significant performance benefits, since more ONUs have the opportunity to select higher-order modulation formats.

Finally, long reach networks have also been evaluated for increased ONU numbers reaching up to 256 under a distance of 100 km. The long reach SDSCA algorithm utilized efficiently the prolonged idle periods of the network links, demonstrating high throughput and low packet-delay figures.

Abbreviations

3DTV	3-Dimensional TV
10GEPON	10 Gbit/s Ethernet PON
ACCORDANCE	A Converged Copper-Optical-Radio OFDMA-based Access Network with high Capacity and flexibility
ADC	Analogue-to-Digital Converter
ASM	Adaptive Subcarrier Modulation
AWG	Array Waveguide Grating
BS	Base Station
CO	Central Office
CoS	Class of Service
CP	Cyclic Prefix
DAC	Digital-to-Analogue Converter
DBA	Dynamic Bandwidth Allocation
DBPSK	Differential Binary Phase Shift Keying
DFB	Distributed Feedback laser
DQPSK	Differential Quadrature Phase Shift Keying
DS	Downstream
DSCA	Dynamic SubCarrier Allocation
eNB	E-UTRAN NodeB
EPON	Ethernet PON
FPGA	Field Programmable Gate Array
FSCA	Fixed SubCarrier Assignment
FTTB	Fibre to the Building
FTTC	Fibre to the Curb
FTTH	Fibre to the Home
GPON	Gigabit PON
IFFT	Inverse Fast Fourier Transform
IM-DD	Intensity-Modulation and Direction-Detection
LPF	Low Band-Pass Filter
LTE	Long Term Evolution
MAC	Medium Access Control
MAT	Minimum Average Time
MPCP	Multi-point Control Protocol
MVL	Minimum Void Left
NG-PON1	Next Generation-PON1
NGPON	Next Generation PON
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLT	Optical Line Terminal
ONU	Optical Network Unit
ONU/BS	Optical Network Unit/Base Station
OSP	Outside Plant
PHY	Physical Layer
PLOAM	Physical Layer Administration and Maintenance
PON	Passive Optical Network
P/S	Parallel-to-Serial
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service

RDSCA	Rectangular Dynamic SubCarrier Assignment
RN	Remote Node
RSSP	Rectangle Search Space Pruning
SCA	SubCarrier Allocation identifier
SDSCA	Sequential Dynamic SubCarrier Assignment
SLA	Service Level Agreement
SP	Service Provider
SR	Status Reporting
SSMF	Standard Single-Mode Fiber
S/P	Serial-to-Parallel
TDMA	Time Division Multiple Access
Tx	Transmitter
UHDTV	Ultra High Definition Television
US	Upstream
VoD	Video on Demand
XGPON	10 Gigabit Passive Optical Network
WDMA	Wavelength Division Multiple Access

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