Evaluation of Dynamic Bandwidth Allocation Algorithms in GPON Networks

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Abstract: In this paper, two approaches for Dynamic Bandwidth Allocation in GPON networks are proposed, and validated through simulations in the OPNET modeler. One approach address a Status Reporting scheme, where the bandwidth allocation originates from the client request. The second use a centralized Non Status Reporting scheme. Furthermore, parameters to cope with variances in the traffic pattern is quantified. The results on performance, scalability and efficiency show that Status Reporting is utilizing the bandwidth more efficient while the Non Status Reporting provides better QoS for real time services.

Key–Words: GPON, dynamic bandwidth allocation (DBA), simulation, status reporting, OPNET

1 Introduction

Bandwidth requirement for providing new services is increasing. Moreover, different types of users have varying needs regarding the amount of bandwidth and transmission delays. Network providers are forced to think about new mechanisms that will distribute the bandwidth among the users and provide high network reliability. That leads to the increased interest in the optical networks suitable for Fiber to the Home (FTTH) and Fiber to the Building (FTTB) solutions. Creation of the networks in which each connected user obtains high QoS, despite the variation of payment is too costly solution. This leads to high requirement for implementing mechanisms that will be responsible for the appropriate sharing of available resources.

One of the access network technologies introducing high throughput, low delays and advanced bandwidth control is Gigabit Passive Optical network (GPON) [1]. GPON is designed to transport Ethernet packets over the optical medium using the GPON Encapsulation Method (GEM) [3]. The physical link is fragmented into GEM frames as specified in [1] [3]. Each downlink frame contains a Bandwidth map (BWMap), with information about allowed transmission times for each Optical Network Unit (ONU) for the future uplink frame. Dynamic Bandwidth Assignment (DBA) algorithm is used to calculate the total bandwidth assigned for end nodes [3].

This paper introduces two different DBA algorithms designed for GPON, namely, status and non status reporting DBA [3] [4], respectively. DBA for GPON networks is not given in ITU-T GPON specifications, and hence often proprietary algorithms are used in OLT equipment. This paper provides a proposal for the DBA algorithms, together with the analysis of the impact of available configurations on the network performance, which has not been heavily researched until now. The research focuses on the network performance, its optimum configuration parameters and QoS that can be delivered to the subscribers with different traffic priorities. GPON network modelling and simulation has been performed using OPNET environment [15]. Related work to PON networks has been carried out in [10–14]

The remainder of this paper is organized as follows: Section 2 provides background knowledge of DBA and traffic types. In section 3, a DBA algorithm is proposed. In section 4, the simulation scenario is described and simulation results are presented in section 5. Section 6 concludes the paper.

2 Dynamic Bandwidth Assignment (DBA)

GPON uses point-to-multi-point connections between central Optical Line Termination (OLT), coordinating network resources and Optical Network Units (ONU) located near the end users. Maximum allowable distance is 20km. Varying raw transmission rates are available:1.24416 Gbit/s uplink, 2.48832 Gbit/s downlink for asymmetric services and 2.48832 Gbit/s uplink and downlink for symmetric services. Due to the high available bandwidth, its allocation is based on the Service Level Agreements (SLA) where Quality of Service (QoS) can be granted according to the demand. GPON is using transmission container (T-CONT) mechanism for provisioning differentiated QoS. T-CONT is the logical connection between OLT and ONU, where multiple T-CONT types can be allocated in one ONU. GPON contains five different T-CONTS ouf of which types 2, 3 and 4 that were feasible for dynamic bandwidth allocation were evaluated:

1. **T-CONT type 1** for fixed rate traffic sensitive to jitter and delay.

2. **T-CONT type 2** for on-off type traffic with well defined bitrate and strict delay requirements is provisioned with assured bandwidth. This bandwidth has to be granted to the T-CONTs' traffic, if requested. If not used, bandwidth can be reallocated to other T-CONTs, providing that it is available as soon as T-CONT type 2 requires it.

3. **T-CONT type 3** is provisioned with assured bandwidth and additionally, it can be granted non-assured bandwidth if all available assured bandwidth is utilized. It is suitable for variable rate, bursty traffic with requirements for average rate guarantee.

4. **T-CONT type 4** has no bandwidth guarantee but it has eligibility in best effort bandwidth sharing. It is suitable for variable rate, bursty traffic with no delay sensitivity.

5. **T-CONT type 5** is consolidation of other T-CONTs, provisioned with both fixed and assured bandwidth.

Collisions in such high throughput networks are very costly. In order to avoid collisions the OLT allocates upstream transmission intervals per T-CONT in a TDMA fashion. Transmission is coordinated using GPON Transmission Convergence (GTC) frames in both uplink and downlink direction. In downstream frame, OLT transmits BWMap containing timing information indicating when each T-CONT is allowed to transmit data during future upstream frame. The DBA automatically adjusts bandwidth grants to the needs of a particular T-CONT. The DBA uses the T-CONT's activity status as an input to the scheduler. This activity status can be obtain either explicitly through T-CONT buffer status reporting (SR), or implicitly through transmission of the idle GEM frames when T-CONT does not have enough data to transmit during all granted upstream allocation intervals. The implicit method is referred to as non status reporting (NSR). Assured bandwidth is granted regardless of the overall traffic load. Additional non-assured and best effort bandwidth allocation depends on the available upstream capacity remaining after allocation of the granted bandwidth. Non-assured and Best effort bandwidth can be overbooked, while this can never be the case for assured bandwidth. During bandwidth allocation the following prioritization is applied:

- Fixed traffic (highest priority)
- Assured traffic
- Non-assured traffic
- Best effort traffic (lowest priority)

For both SR and NSR DBA, the OLT traces the activity status of each T-CONT during one DBA cycle. Obtained information becomes input to the scheduler, which thereby allocates transmission opportunities for the next DBA cycle.

3 Proposed Dynamic Bandwidth Assignment Algorithms

3.1 Non Status Reporting DBA

In the NSR algorithm, the OLT estimates bandwidth allocation for the next DBA cycle $B_a^t(c)$, required by each T-CONT t, on the basis of the bandwidth usage during the previous DBA cycle $B_u^t(c-1)$.

At the beginning of each cycle c, at first the OLT assigns assured bandwidth for each T-CONT t $(B_a^t Asr)$, based on the amount of data transmitted in the previous cycle. After this assignment, remaining GPON bandwidth is divided between non assured traffic $(B_a^t Nasr)$. In the end the rest of available bandwidth is distributed for the best effort traffic $(B_a^t BE)$. The assured bandwidth granted for T-CONTs of type 2 and 3 for the new cycle $B_a^t Asr(c)$ is based on the activity in the previous cycle $B_u^t(c-1)$, as shown in eq. 1. The expansion factor (EF) is used to provide fast response for variation in traffic, and to ensure that assured bandwidth is always allocated when required by a T-CONT.

$$B_a Asr^t(c) = \begin{cases} Max_{asr}^t & \text{if } B_u^t(c-1) = Max_{Asr}^t \\ Min_u^t & \text{if } B_u^t(c-1) \leq Min_{Asr}^t \\ B_u^t(c-1) * EF & \text{otherwise} \end{cases} \quad (1)$$

Equation 1 verifies that $B_a^t Asr(c)$ does not exceed the maximum allowed bandwidth Max_{Asr}^t for T-CONT t and is never lower than the minimum bandwidth Min_{Asr}^t.

Assignment of additional non-assured grants $B_a^t Nasr(c)$ eligible for T-CONTs of type 3 depends both on bandwidth used by the T-CONT in the previous cycle $B_u^t(c-1)$ and assured bandwidth already assigned for current cycle $B_a^t Asr(c)$ (eq. 2). It is limited by the total allowed bandwidth Max_{Total}^t, and no minimum bandwidth assignment is guaranteed.

$$B_a^t Nasr(c) = \begin{cases} Max_{total}^t - Max_{Asr}^t & \text{if } B_u^t(c-1) * EF > Max_{total}^t \\ B_u^t(c-1) * EF - Max_{Asr}^t & \text{if } B_u^t(c-1) > Max_{Asr}^t \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

When the non-assured bandwidth is overbooked, non-assured bandwidth assignments are scaled proportionally to fit into the total link capacity C for each T-CONT (eq. 3)

$$if : (\sum_t B_a^t Asr(c) + \sum_t B_a^t Nasr(c)) > C$$
$$than : \quad (3)$$
$$B_a Nasr^t(c) = \frac{B_a^t Nasrt(c) * (C - \sum_t B_a^t Asr(c))}{\sum_t B_a^t Nasr(c)}$$

Best effort bandwidth is assigned proportionally to $B_u^t Be(c-1)$ scaled by EF(eq. 4), (eq. 6) and limited by Max_{total}. OLT should try to grant to each T-CONT minimum amount of bandwidth in each cycle to avoid T-CONT deadlock situation, where ONU has no means of informing OLT about its bandwidth requirements. In highly overbooked networks zero bandwidth allocation in the previous cycle indicates that the link was too congested to serve the best effort traffic. Therefore $B_a^t Be(c)$ is set to infinity, and scaled equally for all T-CONTs of type 4 (eq. 5).

$$B_a Be^t(c) = \begin{cases} Max_{total}^t & \text{if } B_u^t(c-1) = Max_{total}^t \\ \infty & \text{if } B_u^t(c-1) = 0 \\ B_u^t(c-1) * EF & \text{otherwise} \end{cases} \quad (4)$$

$$if : (\sum_t B_a Asr^t(c) + \sum_t B_a Nasr^t(c) + \sum_t B_a Be^t(c)) > C$$
$$then :$$
$$B_a Nasr^t(c) = \frac{\sum_t B_a Be^t(c) * (C - \sum_t B_a Asr^t(c) + \sum_t B_a Nasr^t(c))}{\sum_t B_a Be(c)} \quad (5)$$

$$B_a^t(c) <-> \frac{B_a^t(c)}{B_u^t(c-1)} \quad (6)$$

When the DBA cycle ends, the scheduler is provided with assignments for a new cycle (eq.1 to eq.5) and creates a bandwidth map for each frame in the new DBA cycle. Assured traffic is allocated for each T-CONT once per millisecond, thereby once in every 8 upstream frames(eq. 7).

$$EF = ceil(\frac{B_a^t Asr(c) * 8}{\text{frames per DBA cycle}}) \quad (7)$$

Non-assured and best effort traffic grants are not served in strictly regular intervals. Bandwidth grant for each T-CONT may occur at most every third frame in order to maximize throughput, since small bandwidth chunks lead to high header overhead and packet fragmentation. Allocations are served in a cyclic manner according to eq. 8 and starting from the T-CONT that was last granted bandwidth.

$$B_{frame} Nasr^t(c) = \frac{B_a Nasr^t(c) * \text{frames since last alloc}}{\text{frames per DBA cycle}} \quad (8)$$

3.2 Status Reporting DBA

In the SR scheduling, the OLT requests the buffer occupancy status from each T-CONT indicating the number of bytes waiting for transmission. At the beginning of a new frame, one T-CONT of each type gets a token. The T-CONT possessing a token is granted allocation slots according to the request, providing that it does not exceed its maximum bandwidth allowed for current cycle. At first, requests for assured allocations are served. Later, bandwidth allocations are given to consecutive non-assured bandwidth requests. In the end, best effort requests are served. After each T-CONT is served, the next in order T-CONT receives the token. At the beginning of a new frame, T-CONTs with tokens received in the previous uplink frames are served first.

4 Simulations

Series of simulations were made using OPNET [15], to evaluate the efficiency of SR and NSR DBA algorithms for varying GPON network scenarios. All GPON physical layer properties [5] together with framing and protocol overheads were accurately modeled. The transmission timing highly affects the results, especially on the SR algorithm, where negotia-

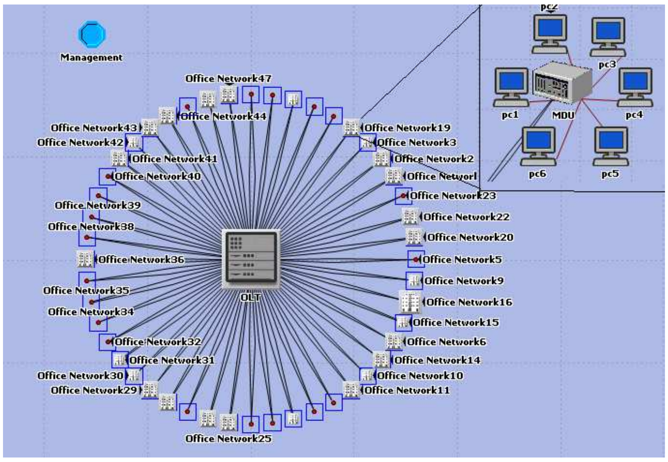


Figure 1: Simulated network.

tion between OLT and ONU has to be performed before calculation of bandwidth grants.

All simulations were performed using GPON 2.48832 Gbps links. No bandwidth is reserved for GPON network control and maintenance, since bandwidth requirement for these control channels is too small to have an effect on the simulation results.

Each ONU has three T-CONTs: type 2, type 3 and type 4. Each T-CONT of same type has the same bandwidth parameters (maximum and minimum bandwidth, source bandwidth). The packet sizes vary for different scenarios, depending on the traffic load generated per workstation. The source load is generated with the normal distribution of variance equal to the average packet size.

In the first part of simulations (A) optimum GPON DBA parameters were determined for SR frequency request, EF and DBA cycle (scenarios A.1, A.2 and A.3 correspondingly). In every case a trade off was to be made, since improvement on one network parameter often results in degradation of the other (increase of bandwidth utilization, results in an increased transmission delay).

Second part (B) provides Fiber to the Building (FTTB) simulation scenarios for observing network performance and traffic QoS for different network configurations. The modelled FTTB topology is shown in in figure 1. The network consists of one OLT and 48 office networks, by which two line cards of OLT are fully utilized. Furthermore, each office network consists of one ONU and six workstations, spaced within 200m from centered ONU node. Two workstations are used to model traffic load of one T-CONT. Each workstation randomly takes a workstation of the same type as a destination. The workstation can be from any network, and one workstation cannot be chosen more than once. The distance between OLT and any of the ONUs is maximum allowed GPON distance of 20 km. FTTB simulation consists of three scenarios:

- **Scenario B.1** was carried out to compare the SR and NSR DBA methods, in the FTTB network with low traffic load. Since bandwidth utilization is not important in such a case, it is the traffic delay (especially uplink delay), that has to be verified.

- **Scenario B.2** models FTTB network, highly utilized with data traffic and with majority of the available bandwidth reserved for the assured traffic of T-CONTs of type 2 and 3.

- **Scenario B.3** is a nearly overbooked network with high utilization by best effort traffic and relatively low assured traffic load.

The following parameters are used to define the network configuration:

- $Assured_{BW}$ - Amount of bandwidth OLT has reserved for a T-CONT. This bandwidth will be given to that T-CONT if required. Otherwise it will be granted to other T-CONTs

- $Source_{BW}$ - Data load generated by one T-CONT. This bandwidth is generated by one or more workstations connected to T-CONT's ONU

- $\frac{Assured_{BW}}{GPON_{BW}}$ - Ratio between bandwidth reserved for high priority traffic of T-CONTs of type 2 and 3, and the GPON link datarate

- $\frac{Source_{BW}}{GPON_{BW}}$ - Ratio between total traffic load generated by all T-CONTs and the GPON link data rate

5 Results

5.1 Network Tuning

Three different sets of simulations were performed to find the most optimum values for SR request frequency, EF and DBA cycle length.

Status Report request frequency SR_{rFreq} indicates how often OLT sends SR request to each T-CONT. If T-CONT is polled for SR too often, it decreases overal system throughput and may lead to incompatibilities between OLT and ONU, due to incorrect timing. On the other hand too seldom SR poll results in increased transmission delays. Results from network simulation with DBA cycle of 32 ms, $\frac{Assured_{BW}}{GPON_{BW}} = 0.63$ and $\frac{Source_{BW}}{GPON_{BW}} = 0.76$ with varying SR request frequency is shown in figure 2.

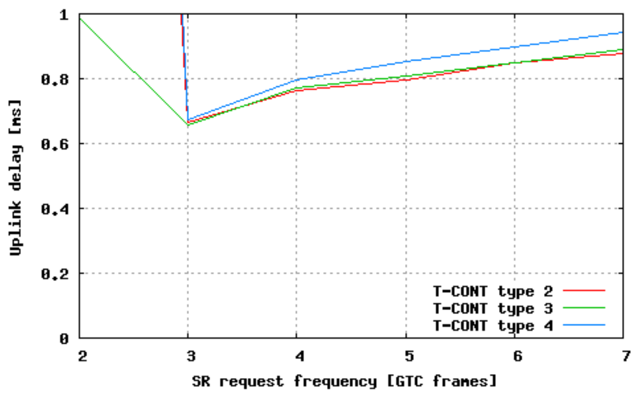


Figure 2: Uplink delay vs. SR frequency

It can be seen that the smallest delay experienced by data belonging to each T-CONT type, is observed with $SR_{rFreq} = 3$, which corresponds to one SR every 3 frames. Lower SR_{rFreq} values result in multiple bandwidth assignment for the same data, and correspond to unacceptable high delays. Higher SR_{rFreq} does not have significant influence on the overall amount of assigned bandwidth as can be seen in figure 3, however it linearly increases the data delay.

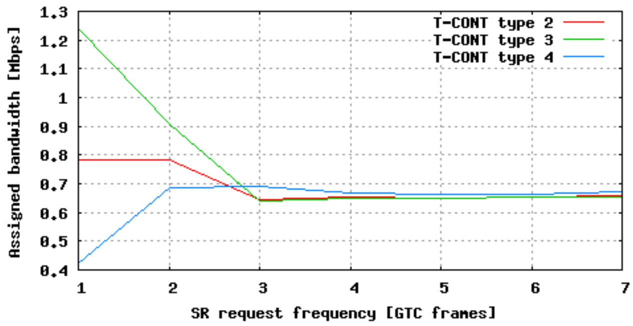


Figure 3: Assigned Bandwidth vs. SR frequency

The Expansion factor EF determines the ratio for the bandwidth assigned for current DBA cycle c to the traffic used in the previous DBA cycle $c-1$. High EF results in greater bandwidth assignments for a T-CONT. This additional bandwidth compensates for the potential variation in the traffic load. The trade off for this lower delay is less efficient use of GPON link, since often this additional bandwidth is not fully utilized. Results from network simulation with DBA cycle of 32 ms, $\frac{Assured_{BW}}{GPON_{BW}} = 0.78$ and $\frac{Source_{BW}}{GPON_{BW}} = 0.7$ with varying EF is shown in figure 4. Decrease in

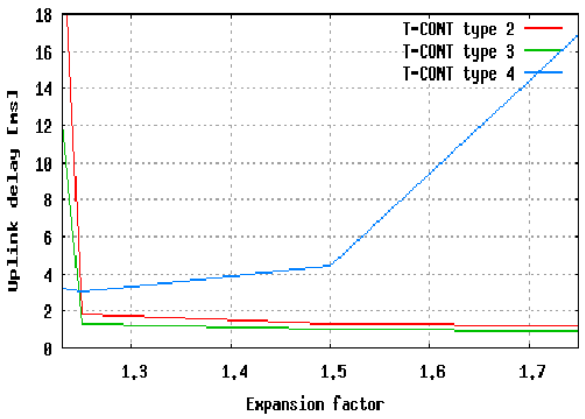


Figure 4: Uplink Delay vs. EF

in link delay of T-CONT types 2 and 3 corresponds to uplink delay increase for T-CONT of type 4, since increased EF provides higher bandwidth allocations for T-CONTs of type 2 and 3, which results in smaller amount of bandwidth left for BE traffic from T-CONT of type 4 as show in figure 5. Expansion factor can never be smaller than or equal to 1, since this would lead to a situation where the bandwidth for future cycle for T-CONTs of type 2 and 3 could either be constant or decrease. This would be an unacceptable case since one cycle with lower data load would lead to reduced bandwidth allocations for future cycles. In performed set of simulations with EF ranging between 1 and 2, 1.25 turned out to be the best value, that would provide reasonable delay for all T-CONT types. Higher EF results in minimal uplink transmission delay decrease for T-CONTs of type 2 and 3, and rapid delay increase for T-CONT of type 4. The optimal observed value is 1.25.

DBA cycle length thus determines how often new cyclic bandwidth assignment for all T-CONTs should be recalculated. Results from network simulation with DBA cycle of 32 ms, $\frac{Assured_{BW}}{GPON_{BW}} = 0.78$ and $\frac{Source_{BW}}{GPON_{BW}} = 0.7$ with varying EF is shown in figure 6.

For the short DBA cycle length, T-CONTs of types 2 and 3 suffer higher delays, while T-CONT of type 4 experiences the least delay. The reason for T-CONTs of type 2 and 3 suffering higher delays, is the fact that, when traffic load measurements are taken for a shorter period, they are less uniform. With normal distribution over longer time periods, traffic load tends to be the average value of the normal distribution. The

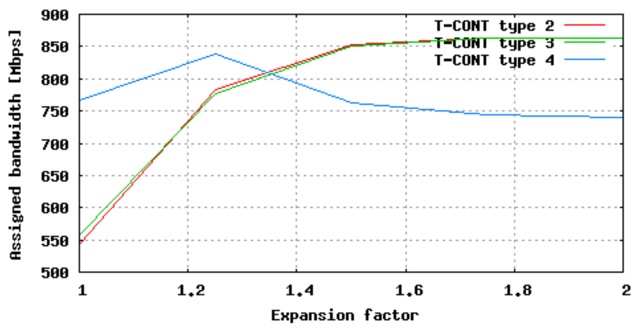


Figure 5: Assigned Bandwidth vs. EF

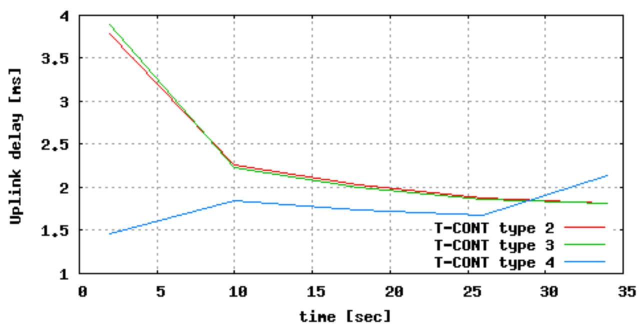


Figure 6: Uplink Delay vs. DBA cycle

shorter the measuring period, the higher variation can be observed. These delay values are not exceeding 5 ms since the cycle length is short and bandwidth assigned per cycle can be relatively quickly recalculated for new frame. Low DBA cycle time corresponds to more varying traffic assignments per cycle, while for larger cycle times they are more stable. For higher DBA cycle, less bandwidth is assigned per cycle, since during longer periods more information is gathered about T-CONTs load.

For T-CONT 4, the short DBA cycle time is better, since all bandwidth remaining after assignments to T-CONTs of type 2 and 3, will be distributed to the T-CONTs of type 4 that have completely utilized traffic assigned in the previous cycle. In order to ensure lowest delays for assured and non-assured traffic DBA cycle should be higher than 26 ms.

5.2 Fiber to the Building (FTTB)

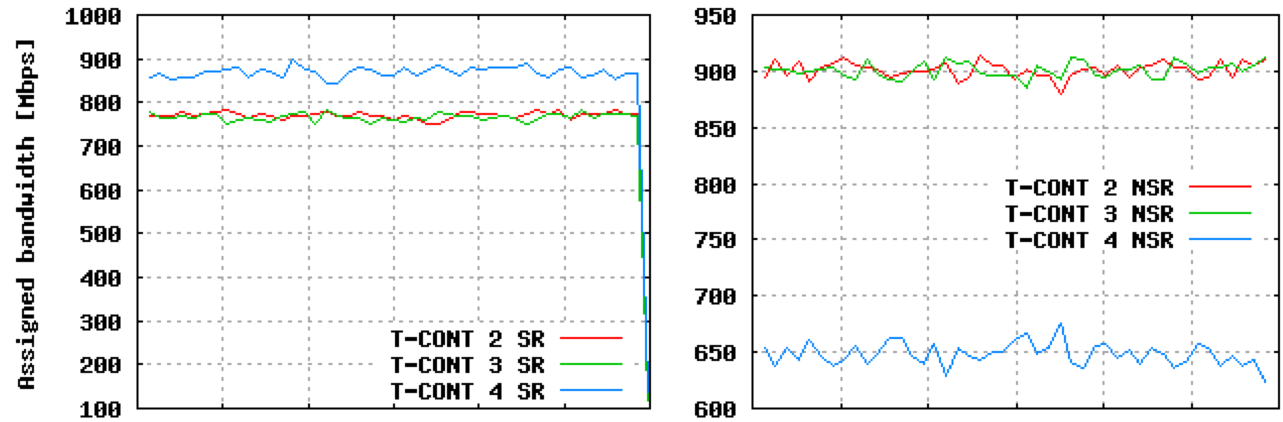
The first FTTB scenario was simulated with the following configuration: $\frac{Assured_{BW}}{GPON_{BW}} = 0.56$, $\frac{Source_{BW}}{GPON_{BW}} = 0.53$ and equal source traffic load for all T-CONTs. It provides a comparison of NSR and SR algorithms with relative low traffic load. The results will show mainly the delay due to the scheduling and physical transmission delays, experienced by the transmitted data. Simulation results show that for the low traffic load of scenario B.1, both NSR and SR algorithms serve all T-CONTs well with the SR average uplink delay of 0.6 ms and NSR of 1.6 ms for all T-CONT types. Delay obtained using SR algorithm is lower, since OLT provides almost immediate response for data transmission request. Delay using NSR algorithm is higher since bandwidth for assured and best effort traffic is allocated every 1 ms.

Scenario B.2 shows NSR and SR algorithm performance with high traffic load. The following configuration was used: $\frac{Assured_{BW}}{GPON_{BW}} = 0.82$ $\frac{Source_{BW}}{GPON_{BW}} = 0.89$ and equal source traffic load for all T-CONTs. In congested networks, SR is more efficiently using network resources. With the SR DBA, transmission delays of 0.65 ms for T-CONTs of type 2 and 3 are similar to the slightly loaded network in B.1. Best effort traffic for T-CONT type 4 also experiences very low delay of 1 ms as shown in figure 7(a). Bandwidth utilization with SR reaches 90% of the total available bandwidth. It can be seen that although T-CONT of type 4 is granted the highest bandwidth it experiences highest delay, due to the fact that bandwidth for best effort traffic is assigned from upstream frame leftovers after assignments for other T-CONTs. For that reason T-CONT of type 4 obtains bandwidth grants less regularly, which results in higher delay. This irregularity also causes multiple assignment of bandwidth for the same data. T-CONTs of type 4 are asked for SR every third frame. Since priority is given for T-CONTs of type 2 and 3, T-CONTs of type 4 usually do not get bandwidth immediately after OLT receives their status reports. Bandwidth for data is assigned by OLT one or two frames after receiving information about waiting data in response to the status report. In the mean time, second SR request is sent and T-CONT informs again about data waiting in the queue. The problem occurs if OLT assigns bandwidth for data before receiving second SR request. In this case OLT gets duplicated information about amount of data waiting in the queue. This leads to the duplicated bandwidth grant, which will most likely not be fully utilized by the T-CONT. Certainly T-CONTs of type 2 and 3 may experience the same duplicated bandwidth assignment in congested network. However T-CONTs of type 4 are more vulnerable to such cases, due to its higher serving irregularity. Duplicated bandwidth assignment could be eliminated by introduction of the status request time stamps. OLT should register the time, when the last status report was obtained from a particular T-CONT. This information could be used in order to verify whether any data assignment has been issued for that T-CONT in the mean time.

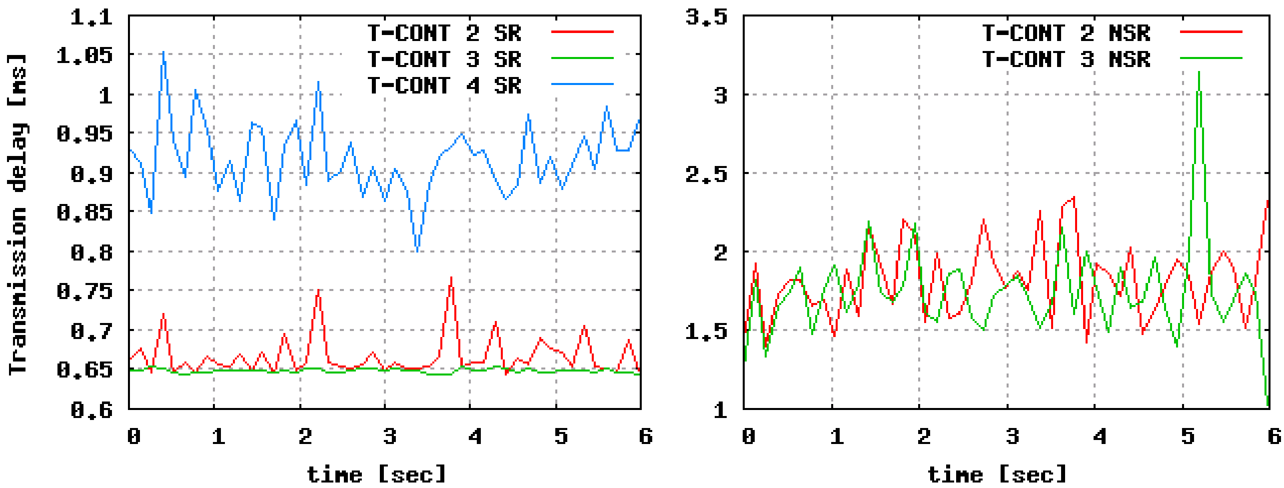
NSR algorithm is slightly less bandwidth efficient, with data bandwidth utilization of 86%. T-CONTs of type 2 and 3 are given more additional but unused bandwidth. As a result not enough bandwidth remains for T-CONTs of type 4. Average of 648 Mbps assigned to T-CONTs of type 4 is not sufficient to serve 744 Mbps source traffic load, as shown in figure 7(a). Considering the fact that again T-CONTs of type 4 often obtain small bandwidth slices left from each frame, their data packets will be heavily fragmented. As a result data throughput for T-CONT of type 4 is very low. 15% of the best effort traffic does not receive bandwidth. In this case transmission delay of that T-CONT type becomes a minor issue.

SR DBA proved to be a better choice for this network configuration, since it offers low transmission delays for both real-time and best effort traffic, and enough bandwidth is assigned for all T-CONT types.

The third scenario B.3 was chosen to test NSR and SR algorithms with high traffic load, dominated by best effort traffic of T-CONT 4. The following network configuration was used: $\frac{Assured_{BW}}{GPON_{BW}} = 0.3$ and $\frac{Source_{BW}}{GPON_{BW}} = 0.9$, source load for T-CONTs 2 and 3 - 432 Mbps each and for T-CONT 4 - 1462 Mbps. Results of the simulation are shown in figure 8(a) and 8(b) . The clear advantages and disadvantages of the two DBA algorithms can be observed in this

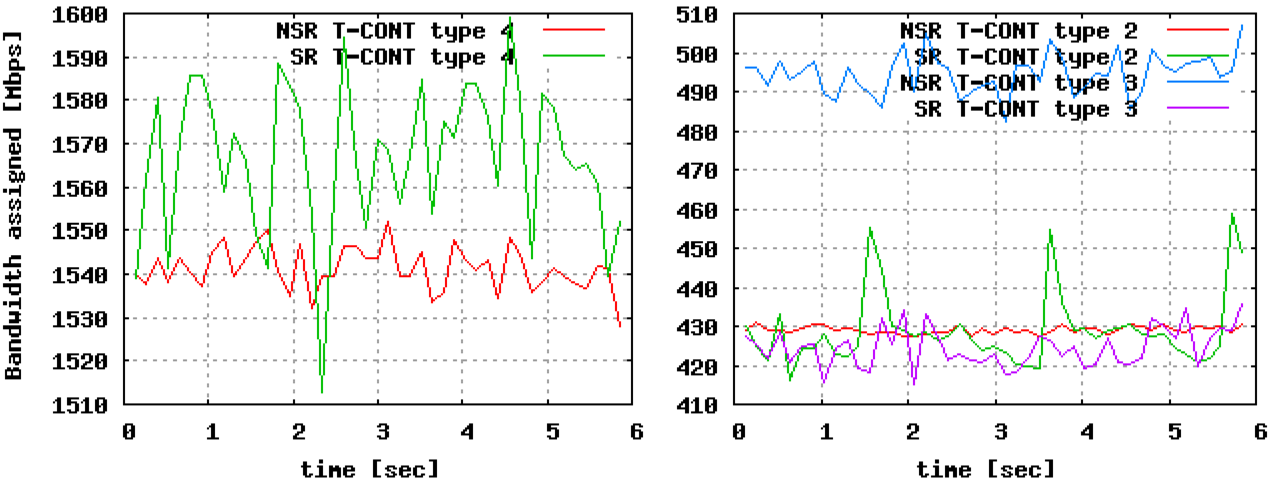


(a) Assigned bandwidth

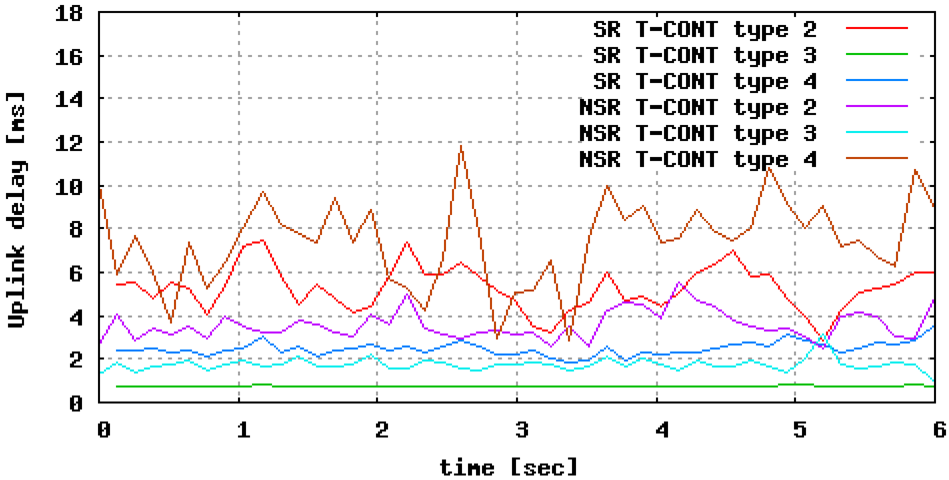


(b) Uplink transmission delay

Figure 7: Simulation results for Scenario B.2.



(a) Assigned bandwidth



(b) Uplink transmission delay

Figure 8: Simulation results for Scenario 3.

high utilized network with high percentage of best effort traffic. In this scenario T-CONT of type 2 assured bandwidth is: $Assured_{BW} = 1.1 * Source_{BW}$

When NSR DBA is used, T-CONTs of type 3 are experiencing smallest delay of average 1.7 ms, while best effort traffic the highest 7.4 ms. T-CONTs of type 3 obtain the best service due to their maximum bandwidth settings. Due to the decrease of safe bandwidth part given to T-CONTs of type 2, they are experiencing slightly higher delay than T-CONTs of type 2. However this average of 3.6 ms delay, is still acceptable, since real-time data requires delay of maximum 5 ms. The maximum bandwidth setting 1.1 times higher than source bandwidth is enough to eliminate the risk of traffic rejection, and it increases the bandwidth utilization to 90%. This utilization is higher than in the previous scenario, where NSR obtained utilization of only 86%. This indicates, that the difference of bandwidth utilization between NSR and SR algorithms is not particularly due to the estimation of bandwidth assignment itself, but mostly due to the additional security bandwidth given to T-CONTs of type 2 and 3.

Bandwidth assignment for the T-CONT of type 3 with NSR DBA is much higher than bandwidth assignment for T-CONT of type 3 with SR. This indicates that T-CONTs of type 3 are granted much more bandwidth when EF is used. Despite the reduction of assured bandwidth for T-CONT of type 2, best effort traffic from T-CONTs of type 4 gets bandwidth assignments irregularly, due to high grants for T-CONT 3. In any case, delay below 10 ms for best effort traffic is sufficient.

The total data utilization of the network is 90%, both for NSR and SR DBA. Over 5 ms delay for T-CONTs of type 2 with SR DBA indicates that this DBA method tends to duplicate bandwidth grants. When new DBA cycle starts and OLT tends to allocate more bandwidth to T-CONT of type 2, due to the congestion in T-CONT's queue. The bandwidth assignment is duplicated from time to time, which leads to reaching maximum bandwidth limit slightly before end of current DBA cycle. Queues get congested, and they are being emptied at the beginning of next cycle, causing duplicated bandwidth assignment. Due to this uneven distribution of bandwidth grants over the cycle in SR DBA, it is necessary to have bandwidth limits slightly higher than the expected source traffic.

NSR DBA seems to be better for the real-time traffic, due to the fact that bandwidth assignments are given regularly every 1 ms. Delay of traffic belonging to T-CONTs of type 4 is, on the other hand, lower than when SR DBA is used (2.4 ms comparing to 7.4 ms).

The NSR DBA delay for T-CONTs of type 3 remains around 1.7 ms, as in previous scenarios. It can be observed that throughout the simulations this tends to be the average value for T-CONTs with a total of assured and non-assured traffic grants not less than 1.25 * source bandwidth. This delay seems to be independent of the traffic load of traffic with other priorities, provided that no overbooking for the high priority traffic has been performed. In order to maintain low delays for real-time traffic, when network is being planned, it should be the amount of assured bandwidth granted for T-CONTs of type 2 and 3, and not the source bandwidth itself, which should be included in the calculation of the load. No overbooking can be made for this bandwidth grants.

6 Conclusion

SR algorighm utilizes bandwidth more efficiently than NSR. In the low loaded networks where a lot of bandwidth is available, SR algorithm allocates around 5% more bandwidth than T-CONTs source load. Efficiency of NSR algorithm depends highly on the expansion factor used, and the assured bandwidth parameter of the T-CONT. If high assured bandwidth is granted, with expansion factor of 1.25, T-CONTs obtain bandwidth grants for up to 129% of the source bandwidth. This security bandwidth allocated for assured traffic is not fully utilized by data. This leads to degradation in throughput for data transmission. Obviously T-CONTs with the lowest priority suffer the highest delay and data drops due to the low bandwidth utilization, since those T-CONTs can only utilize bandwidth chunks left after assignment of assured and non-assured bandwidth grants.

In NSR DBA, the compromise of high QoS for T-CONTs with high priority data and T-CONTs with low priority data is the reduction of the assured bandwidth grants. It was verified that the assured bandwidth parameter set to 110% of the source bandwidth is sufficient to keep the average delay below 5 ms. Low average delay is obtained through the periodical bandwidth allocations, with period of 1ms. This implies that selection of the T-CONT's bandwidth parameters should be performed very carefully, since it is possible for the multiple T-CONT types to obtain reasonable service quality.

If a generic situation is considered, where the system load may vary, the most reliable solution for efficient handling of delay sensitive traffic is NSR algorithm. This is although for low traffic load and high additional bandwidth, delays, using NSR, are higher than the case when SR is used. Regular assignment of grants every 1 ms gives guarantee for appropriate handling. If the generated high priority traffic does not exceed the available bandwidth and no overbooking on assured bandwidth is done, data traffic does not experience delay higher than 5 ms. NSR is not vulnerable to the duplicated bandwidth grants, which implies that bandwidth allocated for each T-CONT is used more efficiently.

Based on the simulation results, it can be concluded that NSR DBA is more reliable in providing agreed QoS, and, with appropriate network configuration optimized for amount of connected ONU's and their traffic requirements, it can sufficiently serve all traffic types. The SR algorithm does not provide and guarantee QoS in all network configurations, but it is efficiently using available resources. NSR is more recommended for networks, where transmission delay has to be maintained below a specified minimum level. This solution however requires more bandwidth due to the over-allocated bandwidth.

The choice of the algorithm should be made depending on the QoS SLAs agreed upon with particular customers and the dominant traffic type in the network.

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