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# Optimization of the Decision Criterion for Increasing the Bandwidth Utilization by Means of the Novel Effective DBA Algorithm in NG-PON2 Networks

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**Abstract:** In this paper, the reasons for the bandwidth and wavelength utilization in future next-generation passive optical networks are presented, and the possibilities for realization and utilization of extended dynamic wavelength and bandwidth algorithms for the second next-generation passive optical networks (NG-PON2) are analyzed. Next, principles of the effective dynamic bandwidth allocation are introduced in detail, focused on the importance of the decision criterion optimization. To achieve a better bandwidth utilization of dedicated wavelengths in NG-PON2 networks, this paper is focused on the novel effective dynamic bandwidth allocation algorithm with adaptive allocation of wavelengths to optical network units as well as the optimization of the decision criterion. The algorithm and the proposed method are tested and evaluated through simulation with actual traffic data. For analyzing novel extended dynamic wavelength and bandwidth algorithms used for various cases of wavelength allocation in NG-PON2 networks, the effective dynamic bandwidth allocation algorithm analysis is realized in the enhancement of simulation program. Finally, an optimization of the decision criterion defining a minimum bandwidth utilization of the actual wavelength is executed for NG-PON2 networks based on the hybrid time and wavelength division multiplexing technique.

**Keywords:** optical fiber networks; telecommunication services traffic control; scheduling algorithms; wavelength channel allocation; numerical simulation

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## 1. Introduction

Demands for high-speed data services and bandwidth applications in business and residual customers are continuously rising every day. Due to coverage potential, cost-efficiency and a high transmission capacity, passive optical technologies are becoming a suitable access network option. Future metropolitan and access networks based on optical fiber technologies must keep capital and operational expenditures as low as possible and provide significantly high transmission capabilities per customer. Therefore, a deployment of the Dense Wavelength Division Multiplexing (DWDM) technique is becoming a reality in future Passive Optical Networks (PON) with its extensive operation in a short time [1,2]. So, the research is focused on the DWDM technique and its effective utilization in passive optical systems and networks.

For the achievement of highly efficient bandwidth and wavelength utilization, it is requested to have advanced Dynamic Bandwidth and Wavelength Allocation (DBWA) methods [3–5] in the Wavelength Division Multiplexing-based Passive Optical Network (WDM-PON) system [6–8] that is incorporated into the F5G architecture. Thanks to wavelength-based optical components, a maximal efficiency of the optical transmission medium utilization can be reached. Therefore, demands of customers for higher transmission capabilities and cost-effective services can be effectively accommodated. Nowadays, several standards for next-generation passive optical networks determine a method of co-operation between various dedicated wavelengths. Moreover, various wavelength transmission channels are available for extended protection schemes in advanced network architectures. For highly efficient bandwidth utilization, extended wavelength allocation methods must be also considered in current and near future hybrid Time- and Wavelength Division Multiplexing-based Passive Optical Network (TWDM-PON) [9–13]. Among other things, Next-Generation Passive Optical Networks (NG-PON) [14–17] provide cost-efficient traffic protection schemes [18–22], whereas fault management is important for uninterrupted internet access services [23–25]. Therefore, NG-PON networks must support the end-to-end protection option for use cases if specified reliability requirements based on user profiles are expected. In the context of network traffic analysis, a discovery of appropriate tools for the evaluation of protection schemes considered as a part of the F5G architecture in future metropolitan and access optical networks is necessary [26–28].

The recent standard for NG-PON2 networks [29] describes only the single wavelength and bandwidth allocation and leaves the multiple wavelength allocation issue to the preferences of network operators. So, effective bandwidth and wavelength allocation algorithms considered for WDM-PON networks present current research challenges of high interest. Given the dynamic nature of data traffic in passive optical networks, it is important to answer the question of how the Medium Access Control (MAC) layer supporting these wavelength channels reacts. The MAC implementation in NG-PON2 networks must take into consideration the intricacies involved in the Optical Line Terminal (OLT) design for any perspective technology to be able to support the dynamic arrangement of Optical Network Unit (ONU) channels. In the passive optical network based on the WDM technique, data traffic from multiple ONU units is multiplexed on available wavelength channels. Considering common demands of wavelength channels, this PON type requests available MAC protocols for coordination of communication between the OLT terminal and ONU units to avoid collisions in data transmission between various ONU units.

In [30], the open problem of MAC implementation in NG-PON2 networks with multiple-line rate channels is highlighted for the first time. A mechanism to provision bandwidth and guarantee a service framework in flexible wavelength spaced system is proposed. In contrast to the downstream traffic, the upstream traffic in the passive optical network based on the hybrid TDM and WDM technique needs an appropriate MAC protocol for avoiding data collisions between ONU units. In such a case, the OLT terminal collects data from ONU units, makes a decision regarding allocated bandwidths and manages the network. Subsequently, a multiple upstream version of the Interleaved Polling with Adaptive Cycle Time (IPACT) was designed. This algorithm expects that each ONU unit supports all possible allocated wavelengths. In a case that the allocated wavelength is not supported by the ONU, then the next available supported wavelength will be allocated.

In [31], an overview on recent developments and progress on standardization in next-generation high-speed passive optical networks is given. An outline of the physical layer as well as the MAC layer functions is discussed. The NG-PON2 network can work in a range of conjugated 100 Gbit/s data rates to provide higher data rates for subscribers. These data rates can also be achieved by multiplexing four wavelengths with the 25 Gbit/s transmission capacity for each. In such a network, the ONU unit needs to be equipped with four fixed wavelength transmitters and must provide a possibility for data transmitting on various wavelengths at the same time depending on the adjusted planning strategy of service network providers. In [32], a novel PON-based architecture is proposed for a mobile backhaul to enhance the connectivity between the neighboring base stations. A tailored MAC protocol and a Dynamic Bandwidth Allocation (DBA) algorithm are introduced to support fast communications between base stations.

In the NG-PON2 network, an OLT terminal allocates bandwidth to ONU units by means of the GRANT control messages in the Round Robin (RR) way. In each GRANT message, the OLT terminal determines Transmission Window (TW) periods for each of the four wavelengths assigned to the ONU unit. This resource allocation is determined using a dynamic bandwidth allocation method realized in the OLT terminal. In the moment of receiving the GRANT message, the ONU unit right away transmits its frames to the OLT terminal. After data transmitting, the ONU unit transmits the REPORT gate for reporting its status of the buffer storage to the OLT. For avoiding data overlapping, the Guard Time (GT) is designated to each wavelength for the separation of data transmitting for various ONU units from each other. For the 25 Gbit/s data rate, the *GT* parameter is considering 1 μs; that presents 3.1250 KB in the data space [32].

For assigning a flexible number of wavelengths to the ONU unit in the NG-PON2 network, an effective dynamic bandwidth and wavelength allocation is requested. If the algorithm of dynamic bandwidth and wavelength allocation is not sufficiently effective, a number of wavelengths and the size of the transmission window for each wavelength can be inappropriately assigned. So, an inadequate transmission capacity of wavelengths can be assigned to ONU units with higher traffic loading. In this case, the delay of packets from the ONU unit will be increased. In another case, more wavelengths can be assigned to ONU units with low traffic loading. Subsequently, the *GT* data space is close to or larger than the *TW* size for each wavelength. As a result, wasteful usage of the upstream bandwidth can influence the network performance by increasing the delay [31,32].

Therefore, effective dynamic bandwidth and wavelength allocation algorithms considered for NG-PON2 networks are at the center of research interests. In [33], two different DWBA algorithms are proposed for the NG-EPON. DWBA-I is a QoS-based algorithm that has been designed to manage several types of data traffic in NG-EPON networks and performs better than different existing DBA algorithms in terms of packet delay, competition time and packet drop ratio. DWBA-II meets the system requirements and specifications of NG-EPON networks, handles the traffic requirements of subscribers in a cost-effective manner and is better than First-Fit DWBA and Modified-IPACT algorithms because of average delay, grant utilization, completion time and packet drop ratio. Neither proposed algorithm is oriented on increasing the bandwidth utilization. In [34], five different DWBA schemes are proposed with diverse customers and prioritized traffic for NG-PON2 systems. Mixed integer linear programming models are developed to minimize a total delay of the high-priority data, and heuristics algorithms are developed based on these models. Proposed schemes with priority class consideration show significant improvement in the total delay of the high-priority data as those are sent first. All the schemes either use single or all wavelengths. The proposed algorithm does not take into consideration that there can be an optimal number of wavelengths to allocate and bandwidth utilization to increase.

On the effective bandwidth utilization of the transmission capacity related to dedicated wavelengths, the following algorithms are oriented. The First Fit Algorithm (FFA) DBA method indexes each wavelength in the NG-PON2 network from 1 up to *W*, where *W* is a number of all wavelengths supported by the optical fiber. This algorithm is looking for free wavelengths in the fixed order. The first available wavelength is selected and no correlation between a spectrum localization and a dedicated index order is needed. An index order can be used for potential improvement of the network performance. Currently used wavelengths are ordered with lower indexes, and, thus, wavelengths with higher indexes can be available for longer transmission paths with higher probability [30].

The First Fit Algorithm is fast and can be utilized in both centralized and distributed network operations. This algorithm has an adequately low blocking and fairness probability, low overhead processing and low complexity. A problem arises in a situation in which the created connections are later cancelled, and an index order cannot guarantee a real wavelength allocation. The FFA index strategy is perceived just as short-term, and it loses its advantages with increasing changes in the network. This algorithm assigns only one wavelength to each ONU unit in each allocation cycle. Primarily, a wavelength that has the earliest starting time will be selected for the upstream transmission. It solves the problem of the delay so that it comes into existence by transmitting data frames on multiple wavelengths in various times and orders. However, the First Fit DBA algorithm cannot accommodate traffic loading variations of different ONU units or changes of active ONU units.

The second Water-Filling Algorithm (WFA) DBA method is based on the Water-Filling approach. In contrast to the FFA, the WFA algorithm tries to balance the utilization of wavelength in each bandwidth allocation. The Water-Filling Algorithm always begins with the earliest starting time for decreasing a difference of starting times for all wavelengths. This means that the FFA algorithm can best work with a high number of ONU units, and the WFA algorithm has the best performance for a small number of ONU units in the NG-PON2 network. Because both algorithms cannot adaptively assign bandwidths on an available wavelength according to varying reported traffic-loading messages from ONU units [30], a key reason for looking for novel Effective Dynamic Bandwidth Algorithm (EDBA) is appearing.

In this paper, the attention is focused on the effective bandwidth and wavelength utilization in future next-generation passive optical networks. In Section 1, principles of dynamic wavelength and bandwidth algorithms in NG-PON2 networks are presented, and reasons for investigating and implementing extended dynamic wavelength and bandwidth algorithms in these networks are analyzed. Section 2 is devoted to the novel effective DBA algorithm with the intention of its implementation in NG-PON2 networks. In Section 3, principles of the EDBA algorithm are introduced in detail, and the optimization of the decision criterion is emphasized. For analyzing novel extended DWBA algorithms utilized for various wavelength allocation cases possible in NG-PON2 networks, a simulation program with the enhancement of the effective DBA algorithm is realized and an optimization of the decision criterion available for future passive optical networks based on the WDM technique is executed in the Section 4. In Section 5, a conclusion with future challenges and research directions are presented.

## 2. The Novel Effective DBA Algorithm for Implementation in NG-PON2 Networks

The Effective Dynamic Bandwidth Algorithm (EDBA) works with the aim of wavelength allocation according to the traffic loading of ONU units. If the ONU traffic loading is higher, then the next wavelength will be assigned so that a transmission window for each wavelength is larger than the *GT* data space in this case. In another case, less wavelengths can be allocated for ONU units with reduced traffic loading. By this method, a number of allocated wavelengths for each ONU unit can be varied in different cycles depending on the reported bandwidth requests and assigned transmission window utilization. If the number of ONU units is small, a maximum upstream bandwidth for one ONU unit can be high-large. In this case, the effective EDBA algorithm is trying to allocate more wavelengths to ONU units. If a number of ONU units is high, then each ONU unit can contribute little to the network traffic loading. In this case, the effective EDBA algorithm can allocate fewer wavelengths to the ONU units based on the effective utilization of assigned transmission windows. By this method, the effective EDBA algorithm guarantees a sufficient bandwidth to each ONU unit and avoids wasteful bandwidth spending caused by redundant *GT* guard times [31,32].

The effective DBA algorithm was introduced for consideration in the first next-generation passive optical networks, however, without the optimization of the decision criterion. No such kind of algorithm is introduced for NG-PON2 networks. Compared to the presented algorithms oriented on the effective bandwidth utilization, the novel EDBA algorithm does not determine fixed wavelengths allocated to all ONU units, but it allows the usage of a flexible number of wavelengths based on the bandwidth utilization of utilized wavelengths. So, the implementation of the novel EDBA algorithm in NG-PON2 networks is the novelty of this work. Moreover, the optimization of the decision criterion is an important part of this implementation due to its direct impact on the bandwidth utilization. Because this algorithm can be implemented in the OLT terminal to avoid upstream data collisions, it increases the upstream latency to an acceptable range.

The EDBA algorithm can adaptively determine a bandwidth and wavelength allocation for each ONU unit based on the starting cycle time for each free wavelength and on the efficiency of the grant utilization on definitively assigned wavelength. The effective EDBA algorithm arranges wavelengths in the ascending order based on their starting time and begins to allocate a bandwidth to a wavelength with the earliest starting cycle time. The next wavelength will be assigned if the transmitting *TW* size is larger than a difference *dif(i)* with the starting cycle time of adjacent wavelength and simultaneously the *TW* size is larger compared to the *Rh* decision criterion and the *GT* data space, where the *Rh* decision criterion is a real number used for defining a grant utilization efficiency [31,32].

The novel EDBA algorithm in NG2-PON networks can be compared with two known DBA methods designed for these networks. For achieving a better bandwidth utilization of the dedicated wavelengths, this work is focused on the effective dynamic bandwidth allocation algorithm with an adaptive allocation of wavelengths to ONU units and on the optimization of the decision criterion that is used for defining a minimum bandwidth utilization of the actual wavelength necessary for possibly allocating the next wavelength. An identification of the optimum decision criterion significantly decreases a time for achievement the effective bandwidth utilization of utilized wavelengths and allows for the adjustment of the *Rh* value at the wavelength allocation process according to the number of connected ONU units.

The NG-PON2 network [29] has an architecture capable of the 40 Gbit/s total network capacity corresponding to four 10 Gbit/s symmetric downstream/upstream data rates available for each wavelength. The NG-PON2 architecture contains simultaneously both time- and wavelength division multiplexing (TWDM) in downstream and upstream directions. For the downstream transmission, four fixed lasers are utilized in the OLT terminal with a wavelength multiplexer. Subsequently, a common light beam is filtered in each ONU unit with active tunable filters that allow a required wavelength for its own receiver. For the upstream transmission, tunable lasers in each ONU unit dynamically assign expected wavelengths. In this way, the utilization of active filters and tunable lasers in the ONU unit is unique. The upstream (1524–1544 nm) and the downstream (1596–1602 nm) wavelength bands are considered for the NG-PON2 system that can provide the 38 dB power budget and can support the 20 km transmission distance with the 1:512 splitting ratio.

For increasing bandwidth utilization of the dedicated wavelengths, the main aim of our research work is oriented on the optimization of the decision criterion that defines a minimum bandwidth utilization of the actual wavelength necessary for possibly allocating the next wavelength. The *Rh* decision criterion is optimized for various numbers of ONU units incorporated into the NG-PON2 network.

## 3. The Optimization of the Decision Criterion in the EDBA Algorithm

The EDBA algorithm works with the dynamic traffic loading of ONU units. When the reported traffic from ONU units is high, the corresponding size of the transmission window is also large. In this case, this *TW* size is larger than the allocated overhead *GT* data space. The EDBA algorithm is trying to divide an ONU traffic to various wavelengths based on their starting times and utilization of the bandwidth allocation. Larger *TW* sizes assigned for each wavelength can avoid large transmission delays. In such a case, the EDBA algorithm allocates transmission windows on all wavelengths because the *TW* size for each wavelength is larger than the *GT* data space. Then, the performance of this algorithm is the same as the Water-Filling Algorithm [31,32].

In general, a higher efficiency of resource utilization decreases in proportion to the reduction in the upstream latency. Right after the data transmission in each ONU unit, its new report with the bandwidth demand in the next cycle is sent. A Grant Processing Time (GPT) is the time taken to process dynamic bandwidth and wavelength allocations in the

OLT terminal that depends on the complexity of the selected method and is now on the order of milliseconds. The waiting time for the bandwidth and wavelength allocation process is considered up to one millisecond; the transition time for the ONU wavelength change is expected to be up to three milliseconds.

When the reported traffic from ONU units is low, the EDBA algorithm is trying to allocate bandwidth requests on a smaller number of wavelengths based on the bandwidth allocation utilization. The bandwidth allocation process begins with a wavelength with the smallest starting time for decreasing the overhead size due to *GT* times. If the reported bandwidth request is smaller than the *GT* data space or less than a decision criterion of the bandwidth allocation utilization, then the EDBA algorithm allocates a bandwidth on one wavelength irrespective of a difference in the starting times of the wavelengths. Then, the EDBA algorithm behaves similarly to the First Fit algorithm. If the reported bandwidth is larger than the *GT* data space or than a criterion of the bandwidth allocation utilization, the next wavelength will be allocated. In such a case, an allocation by using the EDBA algorithm can be executed on any wavelength from the four available. Therefore, the EDBA algorithm allocates a required number of wavelengths to the ONU unit based on the allocation utilization [31,32].

In a moment of the granted allocation, its utilization $\xi$ is calculated from the *TW* size for data transmitting and the *GT* data space using the following formula:

$$\xi = \frac{TW}{TW + GT} \tag{1}$$

For increasing the bandwidth allocation utilization, the *Rh* decision criterion is a crucial parameter because it determines the efficiency of the bandwidth utilization for the dedicated wavelength. This factor is set to 1, the default, at the allocation process and is changed optionally only after evaluation of the bandwidth utilization of utilized wavelengths in the working conditions.

The simulation model is prepared and realized in the MATLAB 2021a programming environment. In this simulation model, parameters presented in Table 1 are included and can be optionally set. The simulation is executed in the online scheduling cycle where the OLT terminal can allocate *i* wavelengths from 1 to 4 to the $ONU_K$ unit based on its reported requested bandwidth *RqB*. It begins with starting cycle times *SC* that are collected and ordered from the smallest to the highest. After ordering, a program calculates a difference of adjacent starting cycle times as follows:

$$dif(i) = SC_{i+1} - SC_i \tag{2}$$

where $i = 1, 2, 3, \ldots$. Next, a residual bandwidth *RsB* of the ONU unit is calculated, whereby *RsB* = *RqB* at the start of the allocation process. A number of wavelengths allocated to the ONU unit is equal to zero ($W = 0$) at the start of the allocation process.

**Table 1.** Parameters of the EDBA algorithm.

| Basic Parameter | Symbol |
|---|---|
| a number of ONU units | *N* |
| a number of actual wavelengths assigned to ONU units | *W* |
| index of ONU units | *K* |
| index of wavelengths | *I* |
| starting cycle times | $SC_i$ |
| a guard time interval | *GT* |
| a requested bandwidth | *RqB* |
| a residual bandwidth | *RsB* |
| a transmission window size | *TW* |
| a difference of starting cycle times | *dif(i)* |
| finishing cycle times | $FC_i$ |

The *GT* parameter is set as a default to 1 μs at the 25 Gbit/s transmission rate corresponding to the 3.1250 KB data space value. Then, the iteration begins if a condition of the EDBA algorithm is satisfied:

$$Rh.GT < TW = \frac{RsB}{W+1} \tag{3}$$

If the *TW* size allocated to the next wavelength is *Rh*-times larger than the *GT* data space, then this concrete wavelength will be allocated (*Rh* = 1 at the start of the allocation process). Otherwise, the requested bandwidth will be divided among the already allocated wavelengths. The next wavelength is added to the *W* parameter, and the number of utilized wavelengths is increased:

$$W = W + 1 \tag{4}$$

If a next wavelength is necessary, then the remaining residual bandwidth *RsB* is uniformly allocated to wavelengths. Consequently, it is divided by $W + 1$. Over the iteration, the residual bandwidth *RsB* is decreasing according to the following formula:

$$RsB = RsB - (dif(i).K) \tag{5}$$

Based on the residual bandwidth *RsB*, a decision about allocating the next wavelength is performed according to the Equation (3). After finishing the iteration, the *TW* size on the allocated wavelength is calculated as follows:

$$TW_i = \sum_{i=1}^{K} dif(i) + \frac{RsB}{K} \tag{6}$$

After determining *TW* sizes on particular wavelengths, starting cycle times of wavelengths for a subsequent ONU unit with its reported bandwidth are calculated and separated by the *GT* data space to avoid collision at the scheduling of the next ONU unit. The formula is used simultaneously for the finishing cycle time *FC* of the previous ONU unit and for the starting cycle time of the next ONU unit:

$$FC_i = SC_i + TW_i + GT = SC_{i+1} \tag{7}$$

For increasing the bandwidth utilization of the dedicated wavelengths, the *Rh* decision criterion must be optimized for a diverse number of connected ONU units.

## 4. The EDBA Simulation Program and Results of the *Rh* Optimization

### *4.1. The EDBA Functionalites*

We prepared a simulation program with real data traffic loading that is utilized for analyzing extended dynamic wavelength and bandwidth allocation methods improving the bandwidth utilization in the NG-PON2 network. This program incorporates the EDBA algorithm in a basic form together with its modifications focused on the bandwidth allocation utilization efficiency. Specifically, the program executes the allocation process managed by the OLT unit in both bandwidth and wavelength areas dynamically for each service cycle. The program also incorporates REPORT messages that present particular requests of the data traffic loading from each ONU unit.

In the presented simulations, we used real data traffic loading from the current GPON network. Four ONU units can operate at 1 Gbit/s, 0.6 Gbit/s, 0.12 Gbit/s and 0.06 Gbit/s data rates in a descending order. Each ONU unit has a reported requested 12 KB bandwidth, and the decision criterion *Rh* has a selected value equal to 1 in the EDBA algorithm, as displayed in Figure 1.

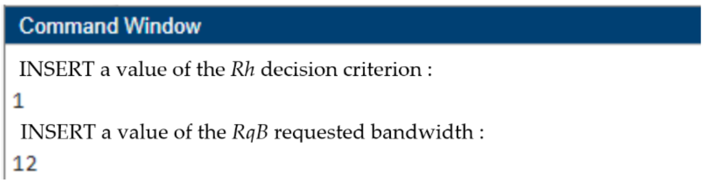


**Figure 1.** The command window with the selection of simulation parameters.

The first ONU1 unit with the 1 Gbit/s data rate reports the 12 KB requested bandwidth. Starting cycle times *SCi* of wavelengths have the 0 KB value at the beginning of the first cycle. The first iteration begins, and the values are compared based on the Equation (3) (3.1250 < 12). In this case, a result is true, and a part of the reported bandwidth is assigned to the first wavelength, as displayed in Figure 2. This part of the reported bandwidth depends on the *Rh* decision criterion and determines a minimum bandwidth utilization of the actual bandwidth.

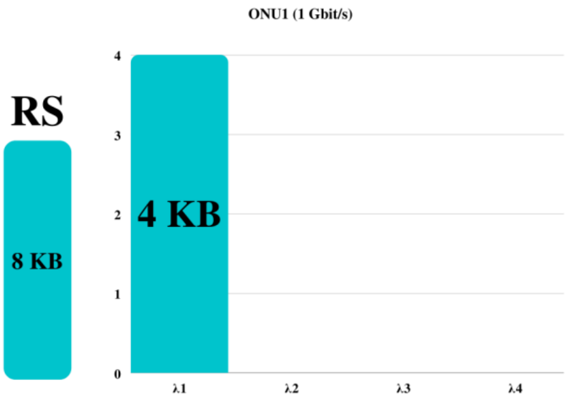


**Figure 2.** The allocated bandwidth of the first wavelength for the ONU1 bandwidth request with a residual bandwidth.

In the next step, the redundant bandwidth is considered for removal based on the Equation (5). However, because starting cycle times of wavelengths are equal to 0, the algorithm waits for iteration based on Equation (3) and adds in sequence a number of wavelengths *W* for assigning to Equation (4) until it reaches a value that does not comply with a condition. In this case, the value *W* is equal to 3 assigned, as displayed in Figure 3.

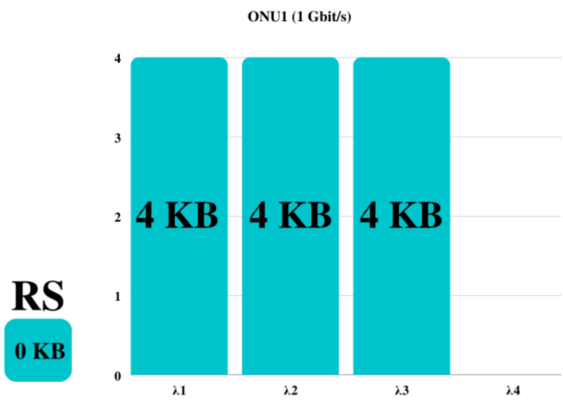


**Figure 3.** The allocated bandwidth of three wavelengths for the ONU1 bandwidth request.

After finishing the allocation process, the *GT* data space equal to 3.1250 KB for each assigned wavelength is added to avoid data collisions. As displayed in Figure 4, a bandwidth allocation based on the EDBA algorithm can save one wavelength compared to the Water-Filling Algorithm that is trying to balance a bandwidth on all four wavelengths. The data transmission from the ONU1 unit takes 32 μs (at the 1 Gbit/s data rate and the 1 μs *GT* guard time) for each of three wavelengths.

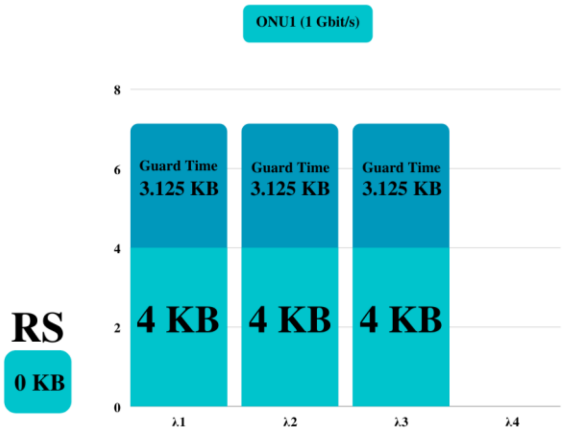


**Figure 4.** The allocated bandwidth of three wavelengths for the ONU1 bandwidth request with the addition of guard times.

The second ONU2 unit has the 600 Mbit/s data rate with the 12 KB requested bandwidth. First, wavelengths are ordered from the smallest starting cycle time $SC_i$ to the highest. Because the fourth wavelength from a previous allocation process is not being used, its starting cycle time $SC_4$ is equal to 0, and it is moved to the first place (Figure 5).

The starting cycle times of wavelengths $SC_2$ for the ONU2 unit correspond to finished cycle times $FC_1$ for the ONU1 unit. Because of a long time difference between the first and second wavelength, an iteration is closed already on the first wavelength based on the Equation (5) and a completely reported bandwidth is assigned to this first wavelength. The data transmission from ONU2 unit takes 160 μs (at the 0.6 Gbit/s data rate and the 1 μs *GT* guard time) on one wavelength. In this case, the EDBA algorithm corresponds to the First Fit algorithm because it occupies only one (first) available wavelength.


**Figure 5.** The allocated bandwidth of four wavelengths for the ONU1 and ONU2 bandwidth requests with the addition of guard times.

A requested bandwidth for the third ONU3 unit is followed with starting cycle times $SC_i$ representing finished times $FC_i$ of the ONU1 unit for three wavelengths and with the ONU2 unit for one wavelength. Moreover, the 12 KB requested bandwidth is reported with the 0.12 Gbit/s data rate. Again, starting cycle times $SC_i$ are ordered from the smallest to the highest as at previous units. Based on the Equation (2), a difference between the values of neighboring starting times of wavelengths *dif(i)* is calculated. At the ONU3 unit, the situation is the same as at the ONU1 unit where a difference *dif(i)* is equal to zero because all adjacent wavelengths have identical starting cycle times.

The assigning of wavelengths for the ONU3 unit depends on the iteration based on the Equation (3), and other wavelengths will be added until a condition in the Equation (4) will be satisfied. Subsequently, the requested bandwidth is uniformly divided into three wavelengths (Figure 6). The data transmission from the ONU3 unit takes 266.7 µs (at the 0.12 Gbit/s data rate and the 2 × 1 µs *GT* guard time) for each of the three wavelengths.


**Figure 6.** The allocated bandwidth of four wavelengths for the ONU1, ONU2 and ONU3 bandwidth requests with the addition of guard times.

The fourth ONU4 unit has the 60 Mbit/s data rate with the 12 KB requested bandwidth. The starting cycle times of wavelengths *SCi* are ordered from the smallest to the highest, and the finished cycle times $FC_i$ of ONU3 and ONU2 units are the starting times of the ONU4 unit.

The assigning of wavelengths for the ONU4 unit is the same as for the ONU3 unit because a difference *dif(i)* is equal to zero (except the last one). The assigning of wavelengths depends on the iteration based on Equations (3) and (4). By this way, a requested bandwidth will be assigned on the first three wavelengths (Figure 7). The data transmission from the ONU4 unit takes 533.3 µs (at the 0.06 Gbit/s data rate and the 3 × 1 µs *GT* guard time) for each assigned wavelength.

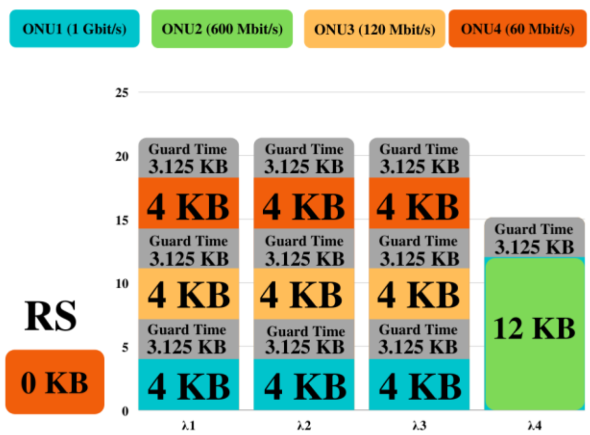


**Figure 7.** The allocated bandwidth of four wavelengths for the ONU1, ONU2, ONU3 and ONU4 bandwidth requests with the addition of guard times.

The EDBA algorithm indicates a characteristic of both the Water-Filling and First Fit algorithms. Compared to the Water-Filling Algorithm, the EDBA algorithm can save six *GT* guard times. Compared to the First Fit Algorithm, the EDBA algorithm can effectively utilize available wavelengths.

### *4.2. The Optimization of the Rh Decision Criterion*

For the efficiency of the bandwidth utilization for the dedicated wavelength, an especially important and crucial parameter is the *Rh* decision criterion. In a previous subsection 4.1, the value *Rh* = 1 is used for keeping more than 50% efficiency at the bandwidth allocation utilization of wavelengths based on Equation (1). In our work, the *Rh* decision criterion is optimized for various numbers of ONU units that can be incorporated into the NG-PON2 network. After multiple runs of the EDBA simulation program, where a number of utilized ONU units is changing and requested bandwidths are stochastically generated based on the real data traffic loading, a number of allocated wavelengths for each cycle is stored, and a median of this number is found. The median is an indicator for a determined number of ONU units, where a value of the *Rh* decision criterion is optimized and simultaneously Equation (1) is allowed. In Figure 8, optimized *Rh* decision criterion values are displayed for diverse number of ONU units.

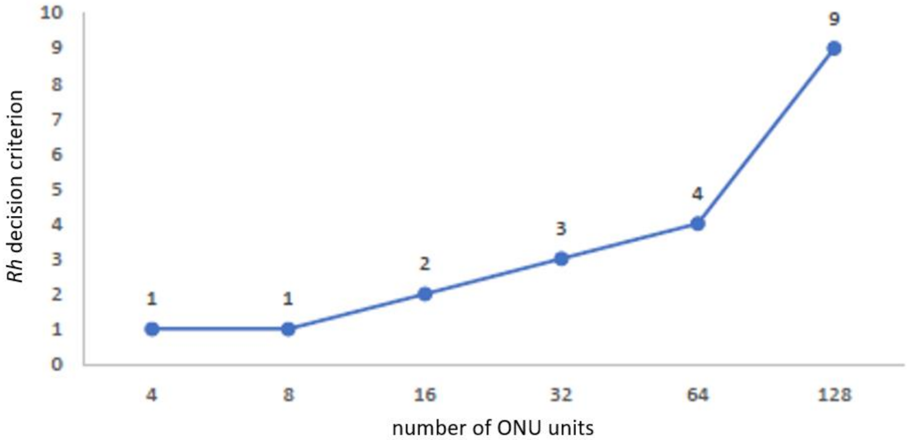


**Figure 8.** A relationship between the number of ONU units and the optimized Rh decision criterion value.

## 5. Conclusions

In this contribution, we present a deployment of next-generation passive optical networks with extensive wavelength utilization and management. For implementations in NG-PON2 networks, the extended dynamic wavelength and the bandwidth allocation algorithms are considered and at the center of research interests. We are focusing on the effective bandwidth utilization of the transmission capacity related to dedicated wavelengths. The effective DBA algorithm is introduced for consideration in the second next-generation passive optical networks together with the optimization of the decision criterion. The novel EDBA algorithm does not determine fixed wavelengths allocated to all ONU units, but it allows the usage of a flexible number of wavelengths based on the bandwidth utilization of utilized wavelengths. So, the implementation of the novel EDBA algorithm in NG-PON2 networks is the novelty of this work. Moreover, the optimization of the decision criterion is an important part of this implementation due to its direct impact on the bandwidth utilization. Based on our simulation results, we can declare that the efficiency of the bandwidth allocation process can be improved, and it is strongly dependent on the optimized *Rh* decision criterion.

The EDBA algorithm based on a wavelength allocation according to the data traffic requests of ONU units allows flexible and effective utilizing network transmission capacities. So, the *Rh* decision criterion applied in the novel effective DBA algorithm considered for the implementation of NG-PON2 networks is optimized in this paper. Therefore, our optimization of the decision criterion supports the utilization of the extended dynamic wavelength and bandwidth allocation methods into future NG-PON2 networks. The value of the decision criterion affects the number of assigned wavelengths during the iteration for one ONU unit and allows the provisioning of a demanded efficiency for the bandwidth allocation process. The results from the EDBA simulation program show that our optimized *Rh* decision criterion is more effective for a larger number of ONU units incorporated into the NG-PON2 networks.

In future works, we can expand a complex view regarding the extended dynamic wavelength and bandwidth allocation algorithms for implementation in NG-PON2 networks in a variety of ways. In these networks, AWG elements in the RN equipment and/or active components in optical end-point terminals can be incorporated. Subsequently, the efficiency of the bandwidth allocation for the dedicated wavelengths must be analyzed in more detail for the larger coverage of metropolitan and access areas, higher numbers of users and higher transmission capacities per user. Furthermore, the attention paid to the selection of the wavelength channels related to a practical utilization in DWDM communication systems can bring other environmental effects—above all, the FWM phenomenon that influences the total network performance in future broadband optical metropolitan and access networks [35,36]. Moreover, the novel effective DBA algorithm, due its effective network resource utilization, can be extended and integrated into the just-in-time wavelength scheduling for providing a higher level of the network wavelength management and control in the OLT terminal.

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