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An Effective Evaluation of Wavelength Scheduling for Various WDM-PON Network Designs with Traffic Protection Provision

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Abstract: Recently, metropolitan and access communication networks have markedly developed by utilizing a variety of technologies. Their bearer communication infrastructures will be mostly exploiting the optical transmission medium where wavelength division multiplexing techniques will play an important role. This contribution discusses the symmetric sharing of common optical network resources in wavelength and time domains. Wavelength-Division Multiplexed Passive Optical Networks (WDM-PON) attract considerable attention regarding the next generation of optical metropolitan and access networks. The main purpose of this contribution is presented by the analysis of possible scheduling of wavelengths for our novel hybrid network topologies considered for WDM-PON networks. This contribution briefly deploys adequate Dynamic Wavelength Allocation (DWA) algorithms for selected WDM-PON network designs with the provision of traffic protection when only passive optical components in remote nodes are utilized. The main part of this study is focused on the use of wavelength scheduling methods for selected WDM-PON network designs. For evaluation of offline and online wavelength scheduling for novel hybrid network topologies, a simulation model realized in the Matlab programming environment allows to analyze interactions between various metropolitan and access parts in the Optical Distribution Network (ODN) related to advanced WDM-PON network designs. Finally, wavelength scheduling methods are compared from a viewpoint of utilization in advanced WDM-PON networks designs.

Keywords: optical fiber communication; WDM-PON network design; wavelength channel allocation; scheduling algorithms; traffic protection

1. Introduction

Originally, communication networks utilizing electronic equipment presented known characters of the symmetry in communications between users. This kind of the symmetry can be observed in co-temporary long-haul communication networks. With a technological development and geographical broadening, a nature of modern communication networks associated with formation of new services and applications is markedly changed, above all in metropolitan and access communication networks. In these networks, a discussion about connection characteristics is in progress. Asymmetrical connections bring important pros in a form of lower prices and fast download speeds. Therefore, they are advantageous for most common users. However, symmetrical connections that allow faster (and larger) file uploads, an elimination of network bottlenecks and accessible cloud services, are very interesting for business customers. Therefore, the aim of advanced metropolitan and access networks based on the optical transmission medium utilizing wavelength division multiplexing techniques is to satisfy different requirements from various types of customers. The correct approach towards fulfilling this aim lies in focusing on another kind of symmetry related to equally matched resource access and sharing. In the case of optical networks, specifically, the equal and symmetric sharing of common resources that are ready for operation means their effective utilization in both time and wavelength domains as much as possible.

Nowadays, the evolution of information and communication technologies is strongly affected by the rapid development of social networks, cloud computing and big data. Bandwidth requirements and demands for the symmetry in connections for metropolitan and access networks are still increasing. To achieve higher bandwidth and better fault tolerance, a variety of interesting technologies are proposed. 5G mobile communication systems provide enhanced services with low latency, high data rate and ultra-reliable communication for internet of things and machine-type communication applications [1]. Wireless sensor networks as one of radio technologies are expected to find interesting smart home, environmental and industrial applications [2]. Low-power and long-range networks aim to solve recurrent processing and energy limitations of smart object devices with wireless communication [3]. Software-defined networks offer a new solution for the legacy network infrastructure. The networking infrastructure is widely implemented with different types of network services and mechanisms. Network monitoring is a method of capturing and carefully inspecting network traffic to determine activation in the network [4]. At present, the optimization of traffic control and flow scheduling for the wireless network load based on software-defined networks has become the focus of attention [5]. In the future of communication traffic, a developing concept of internet of things will play a dominant role in many emerging applications. The importance of transforming the healthcare system into smart healthcare is evolving with its increasing technological demand and aspects [6]. Any considered wireless and mobile technology is developing to be an integral part of communication infrastructures utilizing the optical transmission medium.

In designing optical communication networks, various parameters and network characteristics are necessary taken into consideration, including signal transmission length, traffic protection provision, interconnections between optical network components, a control, a technology [7,8]. The conventional Passive Optical Network (PON) is a bidirectional point-to-multipoint system that contains passive optical elements in a distribution part and active optical components at the end points of the access network. With increasing demand of data rates, it has become necessary to upgrade current optical networks through multichannel approaches. As for the optical metropolitan and access network, a greater capacity can be obtained by using wavelength division multiplexing techniques. The idea to use various transmission channels in metropolitan and access networks is well known [9]. This contribution focuses on the realizable design of the Wavelength Division Multiplexing—Passive Optical Networks (WDM-PON) from a viewpoint of interconnecting schemes. In certain basic variants of WDM-PON architectures [10–12], the wavelength routing is variably utilized. Except changes in the Optical Line Terminal (OLT) fundamental equipment, several stages of splitting points in real WDM-PON network deployment can be included. Thus, the network topology is allowed to be scalable with the number of connected users and to be expandable from the common tree topology to advanced hybrid ones. Therefore, our novel hybrid network topology combines the two-fiber ring topology of the metropolitan part and two-fiber tree topologies of access parts in the advanced WDM-PON network designs. There is a variety of architectures [13] varying in the Remote Node (RN) equipment that present different proposals for implementation in WDM-PON networks. The proposed survivable architectures with the hybrid network topology of passive optical networks are also applicable when more than one stage of remote nodes is realized with only passive components [14].

WDM-PON networks are progressed toward higher bandwidth per user together with higher numbers of users integrated in larger coverage of metropolitan and access areas. The network reliability ensured by implementing of mechanisms for the traffic protection is a substantial need. Therefore, the support of the efficient fault management is essential for network reliability requirements. Thus, a provision of traffic protection must be realized as early as possible [15]. Concretely, traffic protection functionalities should be provided at the time of network deployment. Alternatively, a sufficiency of optical fibers must be installed in advance. For ensuring the signal transmission without network failures, optical single-mode fiber transmission paths require more attention than other components.

Remaining approaches can be more easily installed later, even over the activity of passive optical networks [11,12,16]. The impact of optical fiber duplication utilized in various architectures is analyzed regarding the protection of passive optical networks [17]. For selected Hybrid Passive Optical Network (HPON) architectures, traffic protection schemes in passive optical networks are optimized and an evaluation of traffic protection types with advanced implemented specifications is introduced [16]. In presented WDM-PON network designs with novel hybrid topologies, a provision of the traffic protection in the Optical Distribution Network (ODN) is realized above all by optical fiber duplications in both its parts—metropolitan and access. One of the major challenges is also the effective resource allocation in time and wavelengths because it significantly affects the QoS provisioning in passive optical networks [18]. Moreover, the optical power budget for the accurate provision of the traffic protection schemes must be optimized. For investigating, the optical power budget analysis together with multi-channel compensating techniques related to nonlinear impairments are the focus of interest in nonlinear optical communication systems [19–21].

Based on these assumptions, we realized the analysis of WDM-PON network designs with traffic protection provision from a viewpoint of optimized optical power budgets [22]. In WDM-PON network designs based on novel hybrid network topologies, only passive optical components are the most likely equipment in the RN location where optical fibers from the OLT would be directed to specific ONT terminals. We considered symmetrical power splitters, Optical Add/Drop Multiplexer (OADM) elements and asymmetrical power splitters allowing a creation of wavelength groups. Avoidable optical power budget without waste of the optical power in each access network and with remaining optical power distributed through the metropolitan part to other access networks can be provided only using asymmetrical power splitters with specific ratios. As using asymmetrical power splitters implies grouping of available wavelengths, specific wavelength groups that are created in this way allow the possibility for self-employed work within considered wavelength groups without reference to others. Thus, the network design including asymmetrical power splitters is the most likely option for practical implementations of advanced WDM-PON network designs because a greater number of Optical Network Terminals (ONT) comparing with remaining network designs can be incorporated. Therefore, this architecture can be selected as the option for deployment of Dynamic Wavelength Allocation (DWA) algorithms.

In a previous contribution [22], the evaluation of optical power budgets together with possibilities for their subsequent optimization in advanced WDM-PON network designs with traffic protection provision present its main purpose. Our novel hybrid network topology utilizes working and protection fibers in the ring topology of the metropolitan part and in tree topologies of access parts in the advanced WDM-PON network designs. This contribution continues with a next part of the analysis for advanced WDM-PON network designs that is focusing on the creation, implementation and effective utilization of wavelength groups suitable for WDM-PON networks based on novel hybrid network topologies created by two-fiber metropolitan and access parts in the ODN network. Both contributions create a complex view on advanced WDM-PON network designs utilizing novel hybrid network topologies with related traffic protection securing, optimization of optical power budgets and evaluation of dynamic wavelength allocation algorithms.

This contribution is organized as follows. In Section 2, adequate dynamic wavelength allocation algorithms for selected WDM-PON network designs with traffic protection provision and with only passive components utilized in remote nodes are shortly deployed. We are focusing on dynamic wavelength allocation algorithms, specifically on offline and online wavelength scheduling methods when all wavelengths are ready for operation. Subsequently, flow diagrams of their functionalities are graphically displayed. In Section 3, we focus on methods of wavelength scheduling applicable for selected WDM-PON network designs. For evaluation of offline and online wavelength scheduling, a simulation model is realized in the Matlab software with presented assumptions and simulation parameters.

Based on simulation results for the selected WDM-PON network design No.6, the comparison of offline and online wavelength scheduling is executed. In Section 4, a conclusion with future challenges and research directions is presented.

2. The Deployment of DWA Algorithms for Selected WDM-PON Network Designs

Algorithms for the Dynamic Wavelength Allocation (DWA) can be designed and operated using different approaches related to wavelength scheduling processes [23,24]. A minimization of active wavelength channels considering the high burstiness and delay requirement of fronthaul data transmission in the Centralized Radio Access Network (C-RAN) architecture with the tree network topology using a novel algorithm of bandwidth and wavelength allocation is proposed in [25]. For the Code Division Multiple Access (CDMA)-based passive optical networks with the tree topology where the network throughput and delay requirements per Optical Network Unit (ONU) are relatively moderate, an allocation algorithm based on round-robin scheduling is originally introduced in [26].

Available wavelengths presenting possible transmission capacities must be carefully managed for their effective utilization. For advanced WDM-PON network designs, characteristics and specifications of some wavelength allocation and scheduling methods are introduced in detail in previous work [27]. Implementations of efficient traffic protection mechanisms must be realized for ensuring the network reliability. At the same time, installations of various equipment in remote nodes can be done. In WDM-PON networks with novel hybrid network topologies, the most probably scenario represented with passive optical components in the RN location is only considered. In consequence, an analysis and a comparison of diversified WDM-PON network designs with traffic protection provision must be executed. Simultaneously, characteristics of various protection possibilities for network parts and elements are presented and the optimization of optical power budgets for possible network designs is executed and evaluated. At last, functionalities of selected wavelength scheduling methods are utilized for analyzing considered DWA algorithms.

Dynamic wavelength allocation algorithms are deployed on bandwidth scheduling methods used in TDM-PON networks for the upstream traffic [28,29] including possible wavelength extensions. The Round-Trip Time (RTT) parameter is determined for both optical fibers connecting each ONT terminal. The RTT value presents a time that characterizes a packet transmission through the considered optical fiber (working or protection) from the OLT to the specific ONT and back [30]. Moreover, the minimum bandwidth guaranteed B_{MIN} depends on the w_i weight assigned to each ONT, based on the Service Level Agreement (SLA) between users and the service provider [31]. If a passive optical network incorporates N ONT terminals, then the OLT can allocate the minimum bandwidth guaranteed per cycle B_{MIN} for the ONT-i terminal determined as follows,

$$B_{MIN} = B_i^{MIN} = \frac{\left(T_{cycle} - N.T_g\right).R_N.K.w_i}{Q_R} \tag{1}$$

where T_{cycle} is the granting cycle during which ONT terminals can transmit data and/or send reports to the OLT, T_g is the guard time separating the transmission window for the ONT-i, R_N is the transmission rate in [Mbit/s], K is the total number of wavelengths and Q_R is a number of queue reports per ONT.

Simultaneously a specific wavelength group can include any ONT terminal with regards to its actual possibilities. This integration realized by various ways allows offering a possibility for self-employed work within the considered wavelength group without reference to others. For WDM-PON network designs with novel hybrid network topologies utilizing asymmetrical power splitters, specific wavelength groups in the access network can also be realized with a consideration of their geographic positioning where they are utilized.

Thereafter, a function of the optical fiber in the ODN network can be selected for data transmission between the optical line and network terminals. A primary selection is the working fiber with corresponding parameters for each ONT connection. Only in a case of failure, the protection fiber is utilized with customized wavelength scheduling according to its parameters. The wavelength capacity that defines the maximum transmission rate for specific wavelengths can also assess the Guard Time (GT) specification. The GT parameter can ensure a data transmission without collisions between ONT terminals working on the same wavelength. The GT value presents a period between the last transmitted bit destined for the actual ONT terminal and the first bit destined for the following ONT terminal. In the simulation model, default GT values in the 1 to 5 μs range depend on the wavelength transmission capacity. For presented examples, the 1 Gbit/s transmission capacity per one wavelength is assigned to the working optical fiber and the GT value is equal to 5 μs [31,32]. Different requirements for DWA algorithms that must be satisfied in each ODN network part—metropolitan and access—are defined. The WDM-PON network designs are specifically characterized by utilizing various wavelengths. Moreover, wavelengths can be combined into wavelength groups in some cases. Therefore, any such assumptions must be incorporated when considering DWA algorithms. In a deployment process, a focus is oriented on two methods for wavelength scheduling—offline and online. In following subsections, their functionalities are presented for implementation in selected WDM-PON network designs with using asymmetrical power splitters.

2.1. The Offline Wavelength Scheduling and Its Functionalities

Principles of the offline wavelength scheduling for utilization in advanced WDM-PON network designs with novel hybrid topologies are with more details presented in [27]. This procedure contains the *Inter Scheduling Cycle Gap* (ISCG) interval for decision making. An example for the DWA on the working fiber with the offline wavelength scheduling is displayed in Figure 1 in the simplest form, i.e., individual arrivals of ONT data requests in different time slots. We can see that the ONT-3 unit transmits optical signals on various wavelengths TX λ_1 or λ_2, because its requests are processed last.
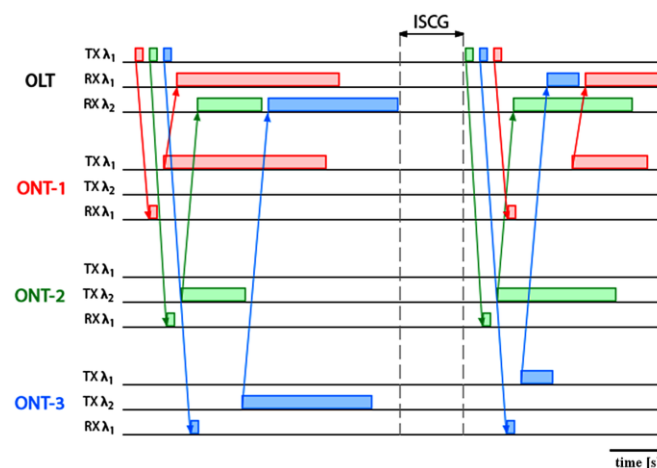

Figure 1. Example of the offline wavelength scheduling in the simplest form.

Functionalities of the offline wavelength scheduling presented in [27] are processed in the simulation model and the simplified flow diagram of the offline wavelength scheduling in the complex form is displayed in Figure 2. In this contribution, free wavelengths are assigning according to the arriving time of ONT data requests. If all wavelengths are occupied, waiting ONT terminals will transmit on released wavelengths, if available, in sequence before the ISCG. After the ISCG, wavelengths are assigned to optical network terminals according to the previously allocated wavelengths. In this way, wavelength changeovers in the ONT are minimized. As an important part of this scheduling method,

attention is also paid to groups of allocated wavelengths. Wavelength groups present possible enhancement of this wavelength scheduling method. When any wavelength group utilizes some wavelengths that are not utilized in other wavelength groups, then wavelengths can be processed separately in each wavelength group. ONT terminals with allocated wavelengths in the specific wavelength group can access to the optical fiber independently on other ONT terminals in other wavelength groups. At the same time, calculating activity is decreased because wavelengths are scheduled only for specific ONT terminals now, not for all active terminals.
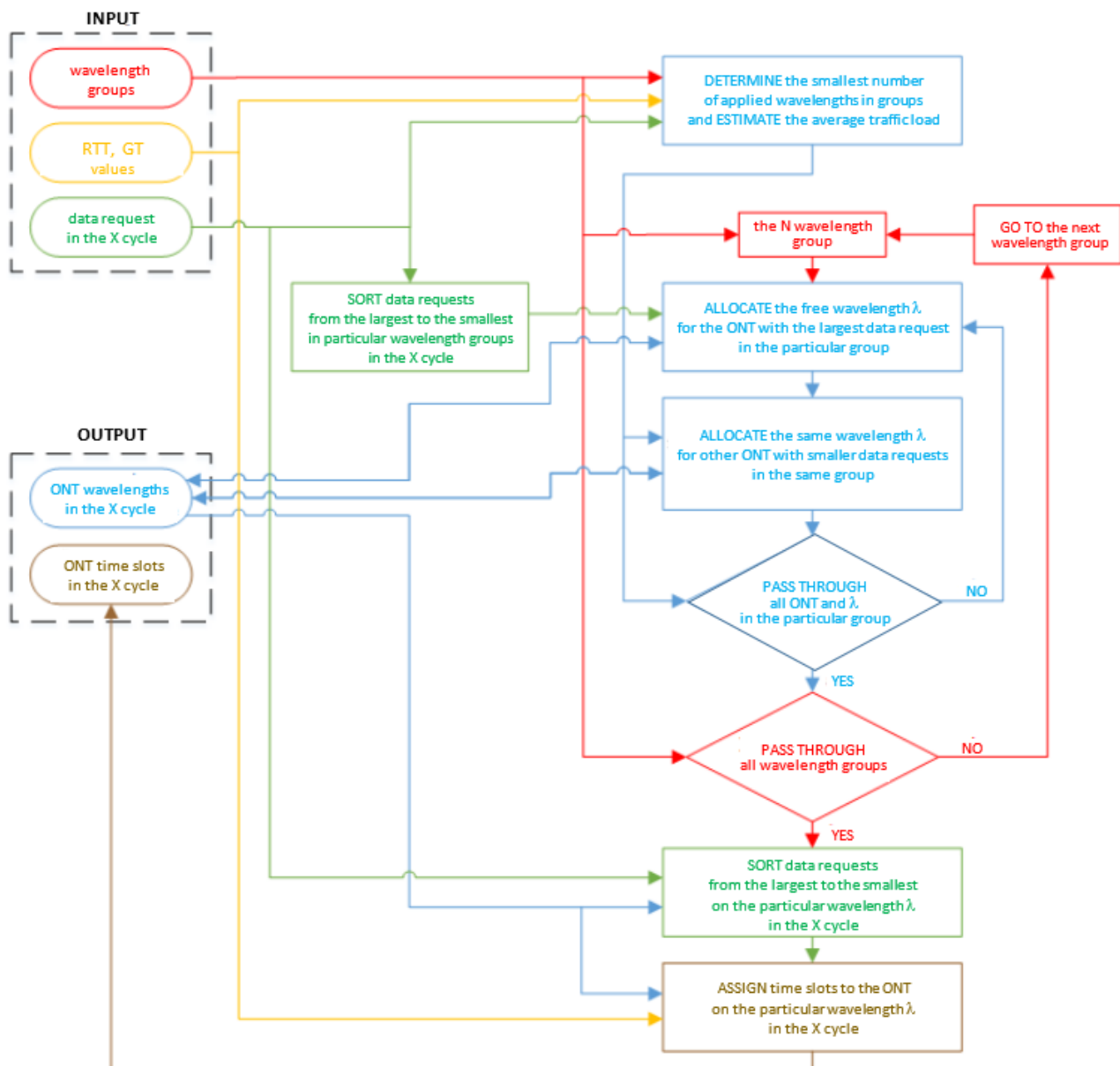
Figure 2. The flow diagram of the offline wavelength scheduling with data requests for transmission in one cycle.

For assignation of transmission windows using the excess bandwidth, there are possible following schemes [31]. In Uncontrolled Excess (UE), the OLT collects reports received from all ONT terminals to determine the excessive bandwidth available for the next cycle. Then, the OLT assigns this total excess equally to all highly loaded ONT terminals regard-

less of their requested bandwidth B_{req}. The total excess bandwidth B^{total}_{excess} is determined as follows,

$$B^{total}_{excess} = \sum_{i=1}^{N} \left(B_{MIN} - B_i^{req} \right) / B_i^{req} \le B_{MIN} \qquad (2)$$

then

$$B_{excess} = B^{total}_{excess} / M \qquad (3)$$

where M is the number of overloaded ONT terminals.

If some ONT terminals are only softly highly loaded, an unfair share of the excess bandwidth that could ultimately not be utilized is highly possible. Hence, the assignment must be realized in Controlled Excess (CE), where the OLT guarantees a fair bandwidth assignment for all ONT terminals.

2.2. Online Wavelength Scheduling and Its Functionalities

Principles of the online wavelength scheduling for utilization in advanced WDM-PON network designs with novel hybrid topologies are presented in more detail in [27]. This procedure is executed without any supplementary interval for decision making. An example of the DWA on the working fiber with the online wavelength scheduling is displayed in Figure 3 in the simplest form, i.e., individual arrivals of ONT data requests in different time slots. We can see that all ONT-i units transmit optical signals on various wavelengths TX λ_1 or λ_2, because their requests are processed immediately.
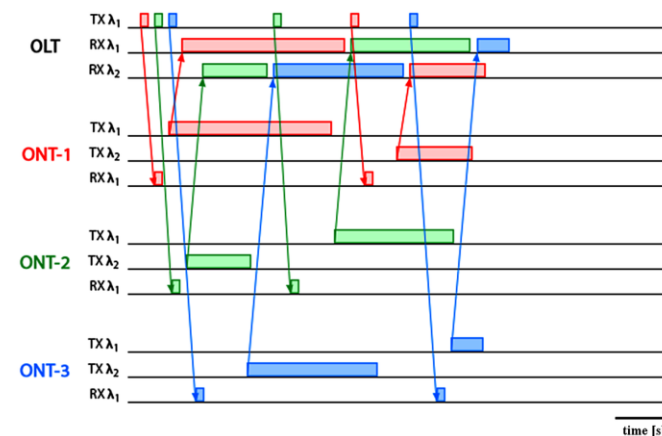

Figure 3. Example of the online wavelength scheduling in the simplest form.

Functionalities of the online wavelength scheduling presented in [27] are processed in the simulation model and the simplified flow diagram of the online wavelength scheduling is displayed in Figure 4. In this contribution, free wavelengths are assigning according to the arrival time of ONT data requests. If all wavelengths are occupied, waiting ONT terminals will transmit on released wavelengths, if available. Since no supplementary interval for decision making is being exploited, wavelengths are assigned to optical network terminals according to arrivals of ONT data requests immediately in sequence. Previously allocated wavelengths are not under consideration. In this way, wavelength changeovers in ONT terminals are very common.

For using the excess bandwidth, a way to assign transmission windows is following [31]. Upon receiving a report from the ONT-I, the OLT checks whether

$$B_i^{req} \le B_{MIN} \qquad (4)$$

In this case, the OLT assigns a gate to the ONT-i terminal immediately. The difference is that lightly loaded ONT terminals can be scheduled directly on the transmission medium without waiting for remaining reports. Furthermore, this early allocation results

in improved delay performance and increased design and implementation complexity. For highly loaded ONT terminals, the OLT waits until other reports from remaining ONT terminals are received and then the OLT assigns a bandwidth for ONT terminals using UE or CE schemes.
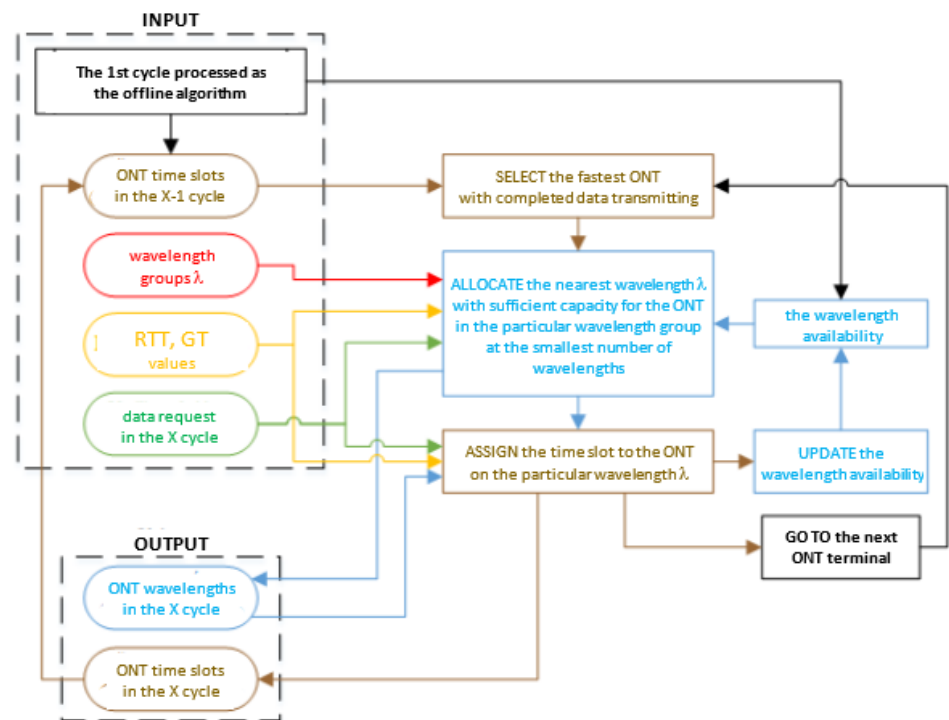

Figure 4. The flow diagram of the online wavelength scheduling with data requests for transmitting in multiple cycles.

3. The Application of DWA Algorithms for Selected WDM-PON Network Designs

After creating the optical distribution network, selected scheduling methods of the dynamic wavelength allocation are applied. The first step for their application is a determination of assumptions and simulation parameters. For analyzing advanced WDM-PON network designs with novel hybrid network topologies, the simulation model created in the Matlab environment is utilized. Its advanced parts allow an optimization of optical power budget possibilities and an effective utilization of the transmission medium in passive optical networks. In this programming environment, scheduling methods of the dynamic wavelength allocation related to the advanced WDM-PON network designs with novel hybrid network topologies are applied. After opening the main window and selecting the simulation purpose, tables with pre-defined parameters for both optical fibers (working and protection) are presented. Based on values of input parameters, possibilities for variable connecting specific access networks with different number of ONT terminals to the ODN metropolitan part are presented. Each possibility of the network connecting is verified and its applicability for the network design with passive elements is determined.

Based on the analysis of resources for advanced WDM-PON network designs with novel hybrid network topologies, the most suitable option involves the one two-fiber ring topology and more two-fiber tree topologies using asymmetrical power splitters [22]. When any of the WDM-PON network designs is selected, the simulation program calculates the required splitting ratios of utilized asymmetrical splitters for each access network for both types of optical fibers—working and protecting. For this contribution [22], optical power level diagrams can be calculated depending on the distance for both working and protecting optical fibers for each ODN access part in the selected WDM-PON network design No.6.

Subsequently, individual parameters characterizing the evaluation of DWA algorithms for both types of optical fibers (working and protecting) in the selected WDM-PON network design can be inserted. Specifically, this concerns the number of ONT terminals connected to the OLT, the transmission rate per wavelength, the guard time, the round trip time, the data waiting for transmitting in all ONT terminals. The condition [31] that a maximum requested bandwidth B_{MAW} does not exceed the wavelength transmission capacity C_λ is established in the form

$$B_{MAX} = B_i^{MAX} \leq C_i^\lambda = C_\lambda \tag{5}$$

Additionally, the time necessary for data transmission $T_{transmit}$ depending on the requested bandwidth B_{req} can be determined for the ONT-I terminal

$$T_{transmit} \leq \frac{B_i^{req}}{C_i^\lambda} \cdot T_{cycle} \tag{6}$$

In this contribution, we are focusing on comparison of wavelength scheduling methods utilized in the WDM-PON network design with our novel hybrid network topology.

3.1. Assumptions and Simulation Parameters

One of the assumptions for successful network communication is the signal transmission without defects caused by bad detections of OLT or ONT equipment because of the network design. Moreover, the signal transmission without failures of working optical fibers is presumptive, although a network design is matched for this situation. Next, ONT terminals designed for the WDM-PON network type are able for communication with four wavelengths in the specific wavelength group.

In the simulation, the number of cycles for data transmission is optional and can be limited to a value of 100. Sequentially, a number of active ONT terminals must be inserted. Active terminals are turned on and ready for data transmitting, if possible. Their number is limited due to possibilities of the selected WDM-PON network design. In the selected network design, ONT terminals are randomly chosen according to a given number. Finally, an option characterizing data transmitting must be done between a manual value insertion and an automatic value generation from the viewpoint of business firms and large buildings, or common customers, or Matlab environment. Every value generation is characterized by setting of probability curves for data requests related to ONT environments. For this contribution, the following simulation parameters were selected in the presented scenarios: 5 cycles for data transmitting, 32 active ONT terminals and automatic value generation for business firms and large buildings. An example of the command window is presented in Figure 5.
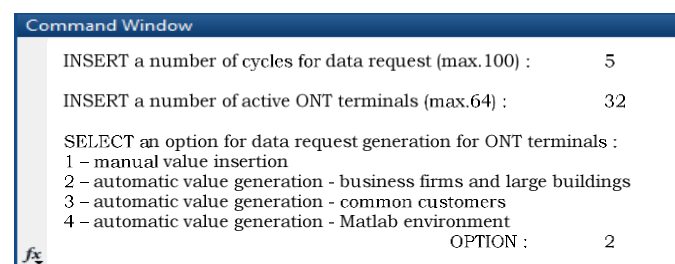

Figure 5. The command window with possibilities and selection of simulation parameters.

3.2. The Simulation of Wavelength Scheduling Methods

After requested value generation, wavelength scheduling methods can be selected and the dynamic wavelength allocation can be executed according to flow diagrams in Figures 2 and 4. After scheduling execution and wavelengths and time slots reservation for ONT terminals in particular cycles for data transmitting, the validation of accuracy for the assigned time slots is activated. This function is focusing on assigned time slots between

ONT terminals in specific wavelengths and it is monitoring the guard time keeping between them. After validation, tables presenting generated values related to the ONT terminals are displayed at first (Tables 1–3).

Table 1. Parameters for the working fiber—distance and RTT.

Working Fiber	Distance [km]	RTT [µs]
ONT-1	6.2353	62.3526
ONT-2	6.7413	67.4135
ONT-3	10.9377	109.3773
ONT-4	2.5073	25.0732
ONT-5	6.4436	64.4365
ONT-6	7.3863	73.9631
ONT-7	1.6776	16.7764
ONT-8	7.7670	77.6697

Table 2. Parameters for the protection fiber—distance and RTT.

Protection Fiber	Distance [km]	RTT [µs]
ONT-1	13.7353	137.3526
ONT-2	14.2413	142.4135
ONT-3	18.4377	184.3773
ONT-4	10.0073	100.0732
ONT-5	13.9436	139.4365
ONT-6	14.8863	148.8631
ONT-7	9.1776	91.7764
ONT-8	15.2670	152.6697

Table 3. Parameters for ONT terminals—data request.

Cycle	Data Requests [Mbit/s]				
	No. 1	No. 2	No. 3	No. 4	No. 5
ONT-1	294	297	212	332	439
ONT-2	320	741	307	508	277
ONT-3	470	384	357	280	258
ONT-4	219	729	92	821	360
ONT-5	372	162	674	460	32
ONT-6	152	38	487	476	743
ONT-7	180	263	54	112	485
ONT-8	285	3	189	498	234

Then, margins and network parameters are displayed according to defined and selected values (Figure 6).

Figure 6. The command window with margins and network parameters according to pre-defined and selected simulation parameters.

Subsequently, time flows for data transmission assigned to ONT terminals in specific wavelength scheduling on the working optical fiber can be displayed in a way that each

ONT terminal has assigned its own color for better visual presentation of results over the complete simulation.

3.3. Results of the Offline Wavelength Scheduling Simulation

In Figure 7, a demonstration of the time flow for signal transmission on the working optical fiber with the offline wavelength scheduling and with focusing on wavelength groups is displayed.
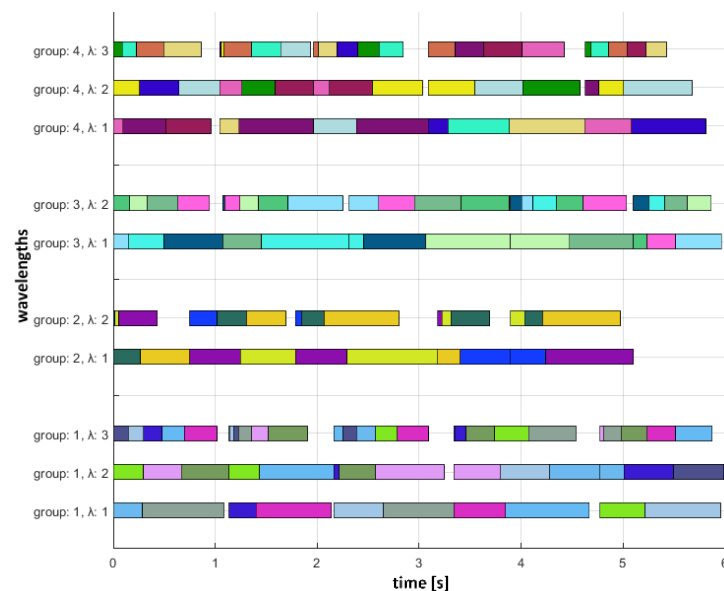

Figure 7. The time flow for signal transmission on the working fiber—the offline wavelength scheduling with focusing on wavelength groups.

In the offline wavelength scheduling, processing cycles are focusing on specific wavelength groups. It means that each group is processed and evaluated independently. In contrast, the conventional offline wavelength scheduling is executed for the data transmitting up to the next cycle all at once for all wavelength groups and ONT terminals. However, this wavelength scheduling is less effective as can be shown in a following comparison to the offline scheduling with focusing on wavelength groups.

For this comparison, the informative processing times of wavelength scheduling and wavelengths and time slots reservation for ONT terminals need to be considered. For the first, the informative time is 31 μs for processing of the conventional offline wavelength scheduling that evaluates all terminals in all wavelength groups all at once. For the second, the average informative time is 7 μs for processing of the offline wavelength scheduling that evaluates each wavelength group independently others. Processing times of the offline wavelength scheduling are expressed by the exponential function of 0 up to 200 μs values characterizing 1 up to 32 ONT terminals. For the last, between receiving last bits of offline wavelength scheduling without and with focusing on wavelength groups, there is a time difference equal to 0.7232 μs. In addition, the improvement at the offline wavelength scheduling with focusing on wavelength groups can be expressed in percentage as 10.8%. Depending on value generation, the average improvement is around 10% for various numbers of cycles and ONT terminals. Based on these results, we will therefore prefer the offline wavelength scheduling focusing on wavelength groups [33,34].

3.4. Results of the Online Wavelength Scheduling Simulation

In Figure 8, a demonstration of the time flow for signal transmission on the working optical fiber with the online wavelength scheduling is displayed.
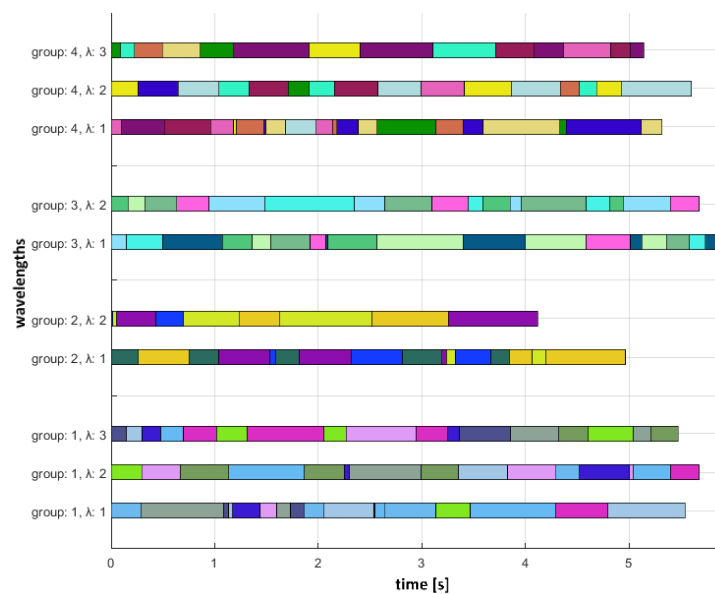
Figure 8. The time flow for signal transmission on the working optical fiber—the online wavelength scheduling.

In the online wavelength scheduling, each ONT terminal is processed independently and immediately in sequence according to its data requests receiving. It means that this wavelength scheduling does not wait for data requests to be received from all ONT terminals and, therefore, no empty time slots occur on wavelengths allocated for data transmitting from ONT terminals, as can be seen in Figure 8, compared to Figure 7.

3.5. The Comparison of Offline and Online Wavelength Scheduling

To numerical presentation of results, a comparison of these wavelength scheduling simulations for the selected WDM-PON network design No.6 is simultaneously presented from the viewpoint of the total calculation time and the number of utilized wavelengths, as can be seen in Table 4.

Table 4. Parameters for offline and online wavelength scheduling—comparison.

Wavelength Scheduling	Offline	Online
Number of wavelengths	10	10
Scheduling time [s]	5.9884	5.8862

For comparison of wavelength scheduling methods, it is necessary to consider the total number of wavelengths utilized over the complete simulation and the total processing time of wavelength scheduling representing a receiving of the last bit from the last ONT terminal in the last processed cycle for data transmitting. Based on our simulation results, we can declare that the total number of wavelengths allocated for ONT terminals is mostly similar for presented demonstrations. Furthermore, scheduling times for both methods are nearly equal. Nevertheless, the offline wavelength scheduling with focusing on wavelength groups is rarely faster in a specific situation. This situation comes into being then if the online wavelength scheduling evaluates if the next transmitted data do not exceed the wavelength transmission capacity. In this way, it is trying to provide for smaller number of wavelengths to other ONT terminals in the next cycle. Therefore, these ONT terminals can transmit data later, and the total processing time of the online wavelength scheduling is increased. The total processing time of the offline wavelength scheduling with focusing on wavelength groups is mostly worse, but it is trying to provide for better QoS provisioning.

4. Conclusions

In this contribution, we present the next part of the analysis for advanced WDM-PON network designs that is focusing on the creation, implementation and effective utilization of wavelength groups suitable for WDM-PON networks based on our novel hybrid network topologies. Based on our simulation results, we can declare that the improvement in the total processing time of the offline wavelength scheduling depends on wavelength utilization in specific wavelength groups. The greater difference between wavelength groups, the better improvement of the offline wavelength scheduling with focusing on wavelength groups. In some cases, the online wavelength scheduling utilizes a larger number of wavelengths than the offline wavelength scheduling with focusing on wavelength groups as a result of the achievement for the wavelength transmission capacity, because ONT terminals at the online wavelength scheduling can transmit data from various cycles in the same moment. Further, the online wavelength scheduling is faster from the viewpoint of the total transmitting time because it reserves wavelengths and time slots for ONT terminals as soon as a data request from the ONT terminal is received and it does not wait on data requests from other ONT terminals.

Both wavelength scheduling methods are adequate and appropriate for utilization in the WDM-PON network with the hybrid two-fiber ring/trees topology, and only network administrators can give priority to either the faster wavelength scheduling or the better QoS provisioning.

In future works, we can expand a complex view over advanced WDM-PON network designs with novel hybrid network topologies in a variety of ways. We would like to also incorporate AWG elements into the RN equipment and/or active components in optical end-point terminals. Furthermore, greater transmission capacities per user, greater numbers of users and larger coverage of metropolitan and access areas can be analyzed in more detail. Moreover, the attention paid to optimization of the wavelength grouping related to terminal localizations can bring other improvements for effective utilization of the optical fiber's transmission capacity in future broadband optical metropolitan and access networks.

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