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The Analysis of Resource Efficiencies for the Allocation Methods Applied in the Proposed OAM&WDM-PON Architecture

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Abstract

Infrastructures of access networks that mostly exploit the optical fiber medium effectively utilizing wavelength division multiplexing techniques play a key role in advanced F5G fixed networks. The orbital angular momentum technique is highly promising for use within passive optical networks to further increase transmission capacities. So, the utilization of common network resources in wavelength and optical domains will be more important. The main purpose of this paper is to present an analysis of resource efficiencies for various allocation methods applied in the proposed OAM&WDM-PON architecture with a conventional point-to-multipoint topology. This contribution introduces novel static, dynamic and dynamic customized allocation methods for a proposed network design with the utilization of only passive optical splitters in remote nodes. These WDM and OAM channel allocation methods are oriented towards minimizing the number of working wavelengths and OAM channels that will be used for compliance with customers' requests for data transmitting in the proposed point-to-multipoint OAM&WDM-PON architecture. For analyzing and evaluating the considered allocation methods, a simulation model related to the proposed P2MP OAM&WDM-PON design realized in the MATLAB (R2022A) programming environment is presented with acquired simulation results. Finally, resource efficiencies of the presented novel allocation methods are evaluated from the viewpoint of application in future OAM&WDM-PONs.

Keywords: passive optical networks; orbital angular momentum; wavelength division multiplexing; allocation methods; WDM and OAM channels; resource efficiency; performance analysis



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1. Introduction

After the invention and implementation of the WDM (wavelength division multiplexing) technique, optical communication networks are rapidly transforming. Nowadays, the WDM operating technology separately or in a hybrid WDM/TDM (Time Division Multiplexing) combination is in use in all optical networks [1–3]. A very promising OAM (orbital angular momentum) technique that is at the center of interest for many researchers [4] seems to be very prospective for use in future optical networks because of further increasing transmission capacities. An interconnection and cooperation of OAM and WDM techniques can be considered a further milestone in the development of information and communication technologies based on optical signal transmission.

2. State of the Art

In recent years, enormous progress in the area of OAM technologies has been made, either in optical communication systems utilizing optical fibers or also in optical wireless propagation in free space environments [5]. It can be considered that OAM deployment is feasible with current technologies. In substance, the OAM technique is a group of higher-order regimes defined on a different base as other mode forms in the optical fiber. Using OAM multiplexing, it is possible to consider the utilization of two different approaches in optical fiber signal transmission. The first approach presents an implementation of the OAM transmission in the common optical FMF (Few-Mode Fiber) transmission medium with a few regimes. The second approach introduces a specially designed vortex fiber that has an interconnection with lower regimes. Thanks to this fact, it is possible to avoid the DSP (Digital Signal Processing) equalizing for relatively short transmission ranges [6]. For the MDM (Mode Division Multiplexing) in common FMF fibers, LP (Linearly Polarized) regimes can be used to achieve impressive results. Each OAM regime presents a linear combination of authentic fiber regimes. Due to faults or other non-idealities, OAM regimes coupled into the FMF fiber can be mutually interconnected. This mutual interconnection of regimes can lead to inter-channel interferences and/or to transmission failures. One possible solution for the regime interconnection effects is the MIMO (Multiple Input Multiple Output) utilization in combination with coherent detection [6]. At the fiber end, received regimes are decomposed based on the OAM ($l = +1$ and -1) regime using the regime sorter. Subsequently, each of the two OAM light components is paired with the PBS (Polarization Beam Splitter) element on the base of polarization fibers. For a reduction in the inter-channel interference, the algorithm with a constant module for blind estimation of the channel crosstalk and its compensation using a linear equalizing is used [6].

In this manuscript, a focus on the proposed WDM-PON architecture involving OAM multiplexing is introduced, and the effective utilization of available wavelength and bandwidth resources in common optical fibers is analyzed. In [7], a novel PON (passive optical network) access architecture based on the OAM multiplexing is proposed and experimentally demonstrated. Multiple data streams can be multiplexed by orthogonal OAM modes on the same wavelength to achieve the efficient utilization of bandwidth resources. This architecture contains the vortex fiber that supports OAM transmission. In the OLT (Optical Line Terminal), the data stream is first modulated onto the optical carrier. The OLT can transmit multi-channel data streams for multiple user access. These multi-channel signals are converted from a fundamental Gaussian beam to the LG (Laguerre Gaussian) beam with various OAM modes. Signals carried by different OAM modes will not interfere with each other [8]. In [9], multiple data channels are multiplexed by mutually orthogonal OAM modes on the same wavelength to realize the efficient utilization of bandwidth resources. The proposed OAM-PON system has the potential to provide flexibility and high bandwidth for large-capacity passive optical networks. In [10], a new hybrid system for high-bandwidth and high-transmission-capacity communication that integrates the MMF (Multi-Mode Fiber) cable with the FSO (Free Space Optics) link using the OAM multiplexing is introduced. This solution can be used for providing services to end users located in remote areas. However, using MMF fiber markedly decreases the transmission distance between the central office and end users' locations. Also, the number of possible subscribers is meaningfully limited compared to common passive optical networks using SMF (Single-Mode Fiber) fibers. In [11], the new-generation PON architecture is proposed and experimentally demonstrated involving the FSO link that also utilizes OAM modes and WDM techniques. Each ONU (Optical Network Unit) receives a dedicated WDM wavelength for the maximum data rate. The separation of OAM modes and wavelength is realized in the optical domain to reduce the end-to-end latency. The experimental setup

deals with downlink signal generation and detection. However, there is no possibility for adaptive wavelength and/or bandwidth allocation in relation to real dynamic traffic loading. In [12], a proposal for the LG mode employing the orthogonal OAM excitation is presented. Simultaneously, a DM (Dimensional Multiplexing) PON system that hybridizes OAM-DM based on the WDM and OFDM is proposed. Effects of different wavelengths and different modes on the BER (Bit Error Rate) are discussed at varying transmission distances. Using the WDM principle, optical fibers can be effectively used also for sensor applications. The paper [13] shows the possibility of using long optical paths to power the polarization sensor. The benefits of fiber optic sensors to be exploited in more applications are presented in [14].

Simultaneously, dynamic allocation methods in both bandwidth and wavelength areas utilized in future advanced WDM-PONs are a center of the research interests. In [15], a novel bandwidth allocation scheme is proposed for the PON system that enables the local area network emulation to determine when to switch its work mode. In [16], DWDM-PONs are considered strong candidates for future optical access networks and the next step in access network development. In [17], a solution to enhance the capacity and efficiency of PONs using dynamic spectrum allocation is presented. This solution relies on the WDM technique. The paper [18] is focused on the DWDM technique and its effective utilization in real optical systems and networks and, consequently, in optical access networks. In this research work, a focus is primarily oriented on novel hybrid network topologies considered for WDM-PONs. The main purpose of the contribution [19] is represented by the analysis of possible wavelength scheduling for selected WDM-PON designs with the traffic protection provision. In these designs, only passive optical components in the RN (remote node) location are utilized, and adequate DWA (dynamic wavelength allocation) algorithms are deployed. In [20], the evaluation of resource efficiencies for the non-symmetric dynamic wavelength allocation method applied in the common point-to-multipoint WDM-PON architecture with a conventional topology is presented. This novel wavelength allocation method is oriented towards minimizing the number of working wavelengths that will be used for compliance with customers' requests for data transmission.

As can be seen, these OAM and WDM techniques can be combined together for potential increases in the transmission capacity of the optical fiber. This solution can be applied in situations where a high capacity or a high spectral efficiency on short transmission ranges is requested [8,21].

As introduced, it can be interesting to join these two OAM and WDM approaches. The main aim of this interconnection can lead to possible practical implementation in real passive optical networks. This contribution is oriented to a possible utilization of OAM regimes in advanced WDM-PON optical networks where OAM communication applications are presented in common optical fibers. Also, a novel architecture of WDM-PONs utilizing the OAM technology is proposed.

The paper is organized as follows: Section 2 is reserved for the State of the Art. In Section 3, a proposal for the common OAM&WDM-PON design is introduced. A simplified network architecture in the P2MP (point-to-multipoint) topology is introduced together with the basic principles of optical signal transmission in both OLT and ONT (Optical Network Terminal) terminals. Due to enormous increases in optical fibers' transmission capacities, I focus on the effective utilization of available wavelength and bandwidth resources in the proposed P2MP OAM&WDM-PON architecture by means of advanced WDM and OAM channel allocation algorithms. For the evaluation of novel allocation algorithms, a simulation model realized in the MATLAB programming environment is presented in Section 4. The development of novel allocation algorithms, together with their assumptions, input parameters, functions of auxiliary calculations, and output param-

ters of algorithms, is specified. Subsequently, particular algorithms for static allocation, dynamic allocation, and the dynamic customized allocation of available WDM and OAM channel resources are characterized in detail. In Section 5, results of different allocation algorithms for different considered operating technologies in common optical fibers are presented based on simulation scenarios for the P2MP OAM&WDM-PON architecture. Simultaneously, resource efficiencies for static, dynamic, and dynamic customized methods are determined. Subsequently, the evaluation of particular allocation algorithms for different operating technologies is executed. Obtained results are discussed in detail appropriately to other published works in Section 6. In the final Section 7, conclusions with future challenges and research directions are presented.

3. The Proposed OAM&WDM-PON Architecture Design with the P2MP Topology

In this section, a proposal of the WDM-PON architecture based on the OAM multiplexing is introduced with the P2MP topology. In this design, multiple data streams are multiplexed by orthogonal OAM regimes on the same wavelength for achieving the effective utilization of the bandwidth resources. Experimental results confirm the high potential of the suggested network architecture for user service provisioning with flexibility and bandwidth efficiency in future ultra-high capacity WDM-PONs [7].

In Figure 1, the access WDM-PON architecture based on the OAM multiplexing is displayed. This architecture consists of the OLT, the RN, and the ONT network elements. The interconnection between the OLT and RN is realized by the common optical fiber supporting the OAM transmission when compared with conventional P2MP WDM-PON architectures [19,20]. In the OLT, network data streams are first modulated on the optical carrier. The OLT can transmit multiple wavelength channels from various users or a single channel for multicasting, depending on the application's demands [7]. The interconnection between OAM TX/RX and WDM Mx/Dx is the main unique property of the proposed network architecture. The WDM channels' ridge in the given wavelength range with the appropriate channel spacing is generated using the CW (Continuous Wave) source. An optical beam from this CW source is phase- and intensity-modulated for the initial generation of the sideband and divided into even and odd channels by means of the WSS (Wavelength Selective Switch) element. The ridge is subsequently passed through the PDM (Polarization Division Multiplexing) emulator. Then, independent data channels are used for considered OAM regimes [21]. Each data channel is passed through a polarization controller and collimated. Each wavelength path is passed through a q-plate, which generates a polarization-dependent combination of OAM beams. After the WDM Mx/Dx element, data channels are jointly transmitted through the common optical fiber. In the RN, a multi-wavelength signal is split in the $1 \times N$ power splitter and transmitted to interconnected ONT terminals. In the ONT, a user data channel on the assigned wavelength is selected using the tunable OBF (Optical Bandpass Filter) element from the received multi-wavelength signal. Then, the output is collimated and sent through a circular polarizer comprising a quarter-wave-plate and a linear polarizer [21]. The SLM (Spatial Light Modulator) element converts a detected OAM mode, after which the optical beam is sent to an optical modulator handling demodulation and error counting. Finally, the receiver receives the appropriate wavelength channel.

For the effective utilization of available wavelength and bandwidth resources in the proposed P2MP OAM&WDM-PON design, novel advanced WDM and OAM channel allocation algorithms can be considered and proposed. For their evaluation, a simulation model related to the proposed P2MP OAM&WDM-PON architecture is realized in the MATLAB programming environment. In this simulation model, novel algorithms for various—the

static, the dynamic, and the dynamic customized—allocation methods can be analyzed for different operating technologies considered. Based on acquired simulation results, resource efficiencies for static, dynamic, and dynamic customized allocation methods are determined and evaluated for different operating technologies considered.

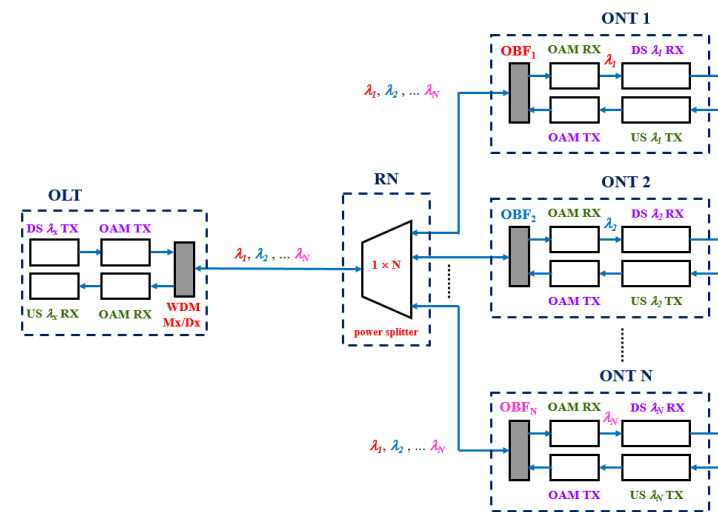


Figure 1. The simplified scheme of the proposed P2MP OAM&WDM-PON architecture.

4. The Simulation Model for the WDM and OAM Channel Allocation Methods in the Proposed OAM&WDM-PON Architecture

4.1. Description of the Development Environment

Considering the fact that there are no suitable present simulation programs, we decided to use the Matlab development environment for realizing a simulation model and for acquiring numerical results. Matlab is an interactive system that represents a tool for highly productive research, development, and analyses in the industry wherein basic data elements are data fields in matrixes and a wide variety of specific application solutions called toolboxes can be utilized [22]. In this programming environment, we created and realized the simulation model related to the conventional OAM&WDM-PON architecture with the P2MP topology. In this model, novel algorithms for allocation methods can be applied. Afterward, resource efficiencies of wavelengths and OAM channels can be analyzed. In the simulation model, a maximum transmission capacity of one wavelength in [Gbit/s] can be determined based on the real GPON (Gigabit-capable Passive Optical Network) of one Slovak telecom operator. Therefore, it is supposed that all utilized wavelengths have the same 10 Gbit/s maximum transmission capacity for realized simulation trials. A value generation of ONT bandwidth requests is characterized by setting probability curves for data requests related to ONT environments. The best option is represented by real traffic loading values related to the Slovak telecom operator's GPON under consideration. Simulations are designed for network services intended for combined residence and office customers and ONT terminals are determined for provisioning three basic customer services. These are IPTV (Internet Protocol Television), HSI (High-Speed Internet), and VoBB (Voice over Broad Band) services. The HSI service operates at the maximum 1 Gbit/s data rate, the IPTV service utilizes the 600 Mbit/s transmission capacity of wavelengths, and the VoBB service can utilize 120 Mbit/s or 60 Mbit/s data rate alternatively. This data is used in the simulation as input parameters for requests of the bandwidth for particular ONUs. Examples of the real GPON traffic loading of Slovak telecom operators are displayed in Figure 2 [20]. Based on the OLT control software application (OptiXaccess EA5801), there is a presentation of the traffic loading of one GPON port all day long.

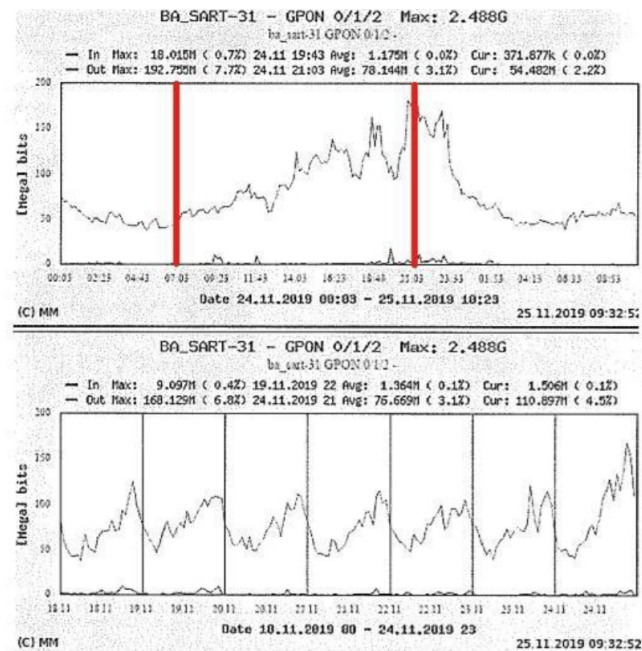


Figure 2. Examples of the real GPON traffic loading all day long.

4.2. Development of Algorithms for Allocation Methods

The aim of this practical part is the creation of algorithms that can demonstrate functionalities for the utilization of the OAM technique in the proposed WDM-PON architecture. Presented algorithms for allocation methods are realized for three possible operating technologies—WDM, OAM, and their OAM/WDM combination. Each considered technology can provide three different allocation methods—static, dynamic, and dynamic customized. Each allocation method can utilize specific functions for setting the simulation program and appropriate input parameters of algorithms.

4.3. Input Parameters of Algorithms

After the program initialization, it is necessary to insert appropriate input parameters. This process is managed by the program. After the first two parameters—a selection of the operating technology and a selection of the allocation method, the possibility of selecting a way for data insertion is allowed. Input parameters can differ in the case of various algorithm selections by reason that some parameters are requested for particular algorithms and unnecessary for others. Definitions of individual input parameters:

- The operating technology *OT*—a selection between WDM, OAM and their OAM/WDM combination; based on the operating technology selection, an option of the algorithm is adapted.
- The allocation method *AM*—a selection between static, dynamic, and dynamic customized allocation method; based on the WDM and/or OAM channel allocation method selection, an option of the algorithm is adapted. The adaptation of the algorithm changes likewise types of resulting data and simultaneously results in a case of permanent data.
- A number of ONUs N_{ONU} —values from 4 up to 256, whereby only squares of 2 are allowed (4, 8, 16, 32, 64, 128, 256). The value is closely related to the number of power splitters' outputs utilized in real telecom operators' passive optical networks.
- The maximum channel transmission rate R_{CH} —values directly in Mbit/s units depending on provided basic customer services (more details can be found in Section 4.1).

- The grant cycle for particular ONUs GC_{ONU} —values directly in μs units; each ONU has dedicated its own value because grant cycles can vary for different ONUs. It depends on the customer service provided by the particular ONU unit.
- The guard time GT —considered in the context of dynamic or dynamic customized allocation methods; a parameter presents a separation window at the transmission between sequential ONUs. The default guard time value is $5 \mu s$.
- The requested bandwidth for particular ONUs BR_{ONU} —values directly in Mbit/s units; each ONU has dedicated its own value because bandwidth requests can vary for different ONUs. The ONU bandwidth request depends on the dedicated customer service (more details can be found in Section 4.1).
- A number of WDM channels N_{Ch-WDM} —considered in the context of WDM or OAM/WDM operating technologies; a range of wavelengths can be from 850 nm up to 1625 nm; after inserting the minimum and maximum wavelengths, a number of WDM channels is calculated based on the maximum channel transmission rate and used various channel spacing possible from 0.1 nm up to 1.6 nm. From the total number of WDM channels, the separate wavelength channel is assigned to ONUs according to the specification in the concrete algorithms. The channel spacing for DWDM applications is based on the standard ITU-T G.694.1 [23] from 12.5 GHz to 100 GHz [18]. The default channel spacing value is 50 GHz, corresponding to the 0.4 nm.
- A number of OAM channels N_{Ch-OAM} —considered in the context of OAM or OAM/WDM operating technologies; a number of OAM channels is dependent on the applied optical fiber's type—a common fiber with 4 OAM channels, the vortex optical fiber with 8 OAM channels and the air core's optical fiber with the 16 OAM channels.
- The SLA (Service Level Agreement) value for particular ONUs SLA_{ONU} —considered in the context of the dynamic customized allocation method; each ONU has dedicated its own value because the SLA value can vary for different ONUs. The SLA value can be from 1 up to 6, whereby it presents a level of telecommunication resource savings. SLA 1 represents a situation where 100% channel transmission capacity is available for 100% requested bandwidth in the case of very prominent customers. SLA 6 represents a situation where the transmission capacity is provided only for the 50% requested bandwidth in the case of common customers. The remaining 50% requested bandwidth is provided only if the transmission channel is not fully engaged.

4.4. Functions for the Auxiliary Calculations

Program parts that are necessary for all algorithms:

- The *Overloaded* function provides a number of overloaded ONUs together with their identification. The ONU is overloaded if its allocated bandwidth is higher than the average ONU load.
- The *Ordered* function realizes an arrangement of ONU bandwidth requests from smallest to largest, whereby the original order of ONUs is unbroken.
- The *Transmitted* function determines the time of data transmission for particular ONUs based on the maximum channel transmission rate and the allocated bandwidth.

4.5. Output Parameters of Algorithms

Each presented particular algorithm contains its own group of output parameters that are displayed after processing of input parameters. Simulation results can be presented in the Matlab command window, stored in xlsx format file, or displayed in graphs. After a presentation of simulation results, original input parameters can be arranged and adapted simulation results can be obtained after re-starting of the selected algorithm.

Definitions of individual output parameters:

- A total number of utilized optical fibers N_{UtilOF} —corresponds to a number of all optical fibers used by the specific allocation method to serve all bandwidth requests of ONUs.
- A number of possible WDM channels per optical fiber $N_{Ch-WDMperOF}$ —presents a maximum number of wavelengths utilized in the optical fiber based on the selected WDM technique; considered in the context of WDM or OAM/WDM operating technologies.
- A number of possible OAM channels per optical fiber/wavelength—presents a maximum number of OAM channels utilized in the optical fiber $N_{Ch-OAMperOF}$ considered in the context of the OAM operating technology or on the wavelength $N_{Ch-OAMperW}$ considered in the context of the OAM/WDM combination.
- A total number of utilized WDM channels $N_{UtilCh-WDM}$ —corresponds to the number of all wavelengths used by the specific allocation method to serve all bandwidth requests of ONUs; considered in the context of WDM or OAM/WDM operating technologies.
- A total number of utilized OAM channels $N_{UtilCh-OAM}$ —corresponds to the number of all OAM channels used by the specific allocation method to serve all bandwidth requests of ONUs; considered in the context of OAM or OAM/WDM operating technologies.
- A number of free WDM channels in the last optical fiber $N_{FreeCh-WDM}$ —provides information about the occupancy state of wavelengths; considered in the context of WDM or OAM/WDM operating technologies.
- A number of free OAM channels in the last optical fiber/wavelength $N_{FreeCh-OAM}$ —provides information about the occupancy state of OAM channels; considered in the context of OAM or OAM/WDM operating technologies.
- A number of active ONUs $N_{ONUactive}$ —a concrete number of ONUs that provide bandwidth requests to be accommodated by the specific allocation methods.
- The efficiency of the WDM channel utilization η_{Ch-WDM} —a ratio of utilized wavelength channels to the total possible wavelength channels.

$$\eta_{Ch-WDM} = \frac{N_{UtilCh-WDM}}{N_{Ch-WDMperOF}} \times 100 [\%] \quad (1)$$

- The possible WDM channel savings σ_{Ch-WDM} —a ratio of free wavelength channels to the total possible wavelength channels.

$$\sigma_{Ch-WDM} = \frac{N_{FreeCh-WDM}}{N_{Ch-WDMperOF}} = 1 - \eta_{Ch-WDM} \times 100 [\%] \quad (2)$$

- The efficiency of the OAM channel utilization η_{Ch-OAM} —a ratio of utilized OAM channels to the total possible OAM channels in the optical fiber $N_{Ch-OAMperOF}$ considered in the context of the OAM operating technology or on the wavelength $N_{Ch-OAMperW}$ considered in the context of the OAM/WDM combination.

$$\eta_{Ch-OAM} = \frac{N_{UtilCh-OAM}}{N_{Ch-OAMperOF/W}} \times 100 [\%] \quad (3)$$

- The possible OAM channel savings σ_{Ch-OAM} —a ratio of free OAM channels to the total possible OAM channels in the optical fiber $N_{Ch-OAMperOF}$ considered in the context of the OAM operating technology or on the wavelength $N_{Ch-OAMperW}$ considered in the context of the OAM/WDM combination.

$$\sigma_{Ch-OAM} = \frac{N_{FreeCh-OAM}}{N_{Ch-OAMperOF/W}} = 1 - \eta_{Ch-OAM} \times 100 [\%] \quad (4)$$

5. Results of the WDM and OAM Channel Allocation Methods

For any selection of the operation technology, the proposed P2MP OAM&WDM-PON architecture is considered. The maximum bandwidth of one WDM channel that can be assigned to an ONU bandwidth request is 1 Gbit/s. This corresponds to the maximum data rate of HSI customer service. From realized simulation trials and efforts with regard to different conditions and input parameters of WDM and OAM channel allocation methods, we selected a presentation of output parameters for the number of ONUs equal to 16 in this section. For WDM channels, the 50 GHz channel spacing is assumed. From the total number of WDM channels, the separate wavelength channel is assigned to ONUs according to the specification in the concrete algorithms. The requested bandwidth for particular ONUs is determined by the dedicated customer service (more details can be found in Section 4.3). These options present a basic and initial version of the simulation model. In the future, a comparison to other allocation methods can be faster and simpler. With an increasing number of ONUs, an increased difference between resource efficiencies for considered allocation methods of WDM and OAM channels, along with associated possible channel savings, can also be expected.

5.1. Algorithms for Allocation Methods Used in the WDM Operating Technology

The WDM operating technology can utilize wavelength channel allocation methods where introduced Algorithms 1–3 present a relatively simple way of the output parameters determination.

As shown in Table 1, the output parameters of three allocation methods were analyzed in the WDM-PON. One of the most important findings that can be presented is the fact that the static allocation method achieves the highest efficiency of the WDM channel utilization η_{Ch-WDM} (more than 50%). On the other hand, two other methods can offer outstanding possible WDM channel savings σ_{Ch-WDM} (85.19% and 88.89%, respectively), more than twice the static method.

Algorithm 1. The Static Allocation Method in the WDM-PON network

1. Loading of input parameters
 2. Functions for the auxiliary calculations
 - 2A. The *Overloaded* function
 - 2B. The *Ordered* function
 - 2C. The *Transmitted* function
 3. The wavelength allocation to the ONU—the separate wavelength channel λ_{ONU_i} is assigned to each ONU
 4. The calculation of the delays D_{ONU_i}
 5. The bandwidth allocation of the requested bandwidth for particular ONU units BR_{ONU_i} on the assigned wavelength λ_{ONU_i}
 6. The calculation of other result values
 7. **If** (Are all ONU served?)
 8. **Then If** (Are there optional functions?)
 9. **Then** The selection of the optional function **And** Go to line 1
 10. **Else End If**
 11. **Else** Go to line 3
 12. **End If**
-

Algorithm 2. The Dynamic Allocation Method in the WDM-PON network

1. Loading of input parameters
2. Functions for the auxiliary calculations
 - 2A. The *Overloaded* function
 - 2B. The *Ordered* function
 - 2C. The *Transmitted* function
3. The wavelength allocation to the ONU—the first wavelength channel λ_1 is assigned to the first ONU
4. **If** (Can be the next ONU_{*i*+1} served by the last assigned wavelength λ_j ?)
 5. **Then** The calculation of the ONU delay $D_{ONU_{i+1}}$
 6. **Else** The new wavelength λ_{j+1} and the zero delay is assigned to the ONU_{*i*+1}
 - And** The calculation of the total wavelength delay D_{total}
7. **End If**
8. The bandwidth allocation of ONU requests $BR_{ONU_{i+1}}$ on the assigned wavelength
9. The calculation of other result values
10. **If** (Are all ONU served?)
 11. **Then If** (Are there optional functions?)
 12. **Then** The selection of the optional function **And** Go to line 1
 13. **Else End If**
 14. **Else** Go to line 4
15. **End If**

Algorithm 3. The Dynamic Customized Allocation Method in the WDM-PON network

1. Loading of input parameters
2. Customization of the ONU requested bandwidth demands according to the SLA values
3. Functions for the auxiliary calculations
 - 3A. The *Overloaded* function
 - 3B. The *Ordered* function
 - 3C. The *Transmitted* function
4. The wavelength allocation to the ONU—the first wavelength channel λ_1 is assigned to the first ONU
5. **If** (Can be the next ONU_{*i*+1} served by the last assigned wavelength λ_j ?)
 6. **Then** The calculation of the ONU delay $D_{ONU_{i+1}}$
 7. **Else** The new wavelength λ_{j+1} and the zero delay is assigned to the ONU_{*i*+1}
 - And** The calculation of the total wavelength delay D_{total}
8. **End If**
9. The bandwidth allocation of ONU requests $BR_{ONU_{i+1}}$ on the assigned wavelength
10. The calculation of other result values
11. **If** (Are all ONU served?)
 12. **Then If** (Are there optional functions?)
 13. **Then** The selection of the optional function **And** Go to line 1
 14. **Else End If**
 15. **Else** Go to line 5
16. **End If**

Table 1. Output parameters of allocation methods in the WDM-PON.

	Static	Dynamic	Dynamic Customized
A total number of utilized optical fibers N_{UtilOF}	1	1	1
A number of possible WDM channels per optical fiber $N_{Ch-WDMperOF}$	27	27	27
A total number of utilized WDM channels $N_{UtilCh-WDM}$	16	4	3
A number of free WDM channels in the last optical fiber $N_{FreeCh-WDM}$	11	23	24
A number of active ONUs $N_{ONUactive}$	16	16	16
The efficiency of the WDM channel utilization η_{Ch-WDM}	59.25%	14.81%	11.11%
The possible WDM channel savings σ_{Ch-WDM}	40.75%	85.19%	88.89%

5.2. Algorithms for Allocation Methods Used in the OAM Operating Technology

OAM operating technology can utilize OAM channel allocation methods in a relatively simple way of the output parameters determination as in the case of the WDM operating technology, where the OAM channels are considered instead of wavelength channels. Therefore, these algorithms are not introduced singly.

Output parameters of three allocation methods analyzed in the OAM-PON are presented in Table 2. The most important finding is that only the dynamic customized allocation method can bring the possible OAM channel savings σ_{Ch-OAM} (25%). Two other methods fully utilize all available OAM channels. The difference is in the number of utilized optical fibers N_{UtilOF} .

Table 2. Output parameters of allocation methods in the OAM-PON.

	Static	Dynamic	Dynamic Customized
A total number of utilized optical fibers N_{UtilOF}	4	1	1
A number of possible OAM channels per fiber $N_{Ch-OAMperOF}$	4	4	4
A total number of utilized OAM channels $N_{UtilCh-OAM}$	16	4	3
A number of free OAM channels in the last optical fiber $N_{FreeCh-OAM}$	0	0	1
A number of active ONUs $N_{ONUactive}$	16	16	16
The efficiency of the OAM channel utilization η_{Ch-OAM}	100.00%	100.00%	75.00%
The possible OAM channel savings σ_{Ch-OAM}	0.00%	0.00%	25.00%

5.3. Algorithms for Allocation Methods Used in the Combination of OAM/WDM Operating Technologies

The combination of OAM and WDM operating technologies can utilize allocation methods for both WDM and OAM channels. So, introduced Algorithms 4–6 combine output parameters determinations from previous algorithms for allocation methods used to a separate operating technology, where first the available OAM channels are allocated, and then the WDM channels are assigned.

Algorithm 4. The Static Allocation Method in the OAM&WDM-PON network

1. Loading of input parameters
2. Functions for the auxiliary calculations
 - 2A. The *Overloaded* function
 - 2B. The *Ordered* function
 - 2C. The *Transmitted* function
3. The channel allocation to the ONU—the first OAM channel OAM_1 on the first wavelength channel λ_1 is assigned to the first ONU
4. **If** (Are all OAM channels served by the actual wavelength λ_j ?)
 5. **Then** The selection of the next wavelength λ_{j+1}
 6. **Else End If**
7. The OAM channel allocation to the ONU—the separate OAM channel OAM_{ONU_i} is assigned to each ONU
8. The calculation of the delays D_{ONU_i}
9. The bandwidth allocation of ONU requests BR_{ONU_i} on the assigned wavelength and OAM channels
10. The calculation of other result values
11. **If** (Are all ONU served?)
 12. **Then If** (Are there optional functions?)
 13. **Then** The selection of the optional function **And** Go to line 1
 14. **Else End If**
 15. **Else** Go to line 3
16. **End If**

Algorithm 5. The Dynamic Allocation Method in the OAM&WDM-PON network

1. Loading of input parameters
2. Functions for the auxiliary calculations
 - 2A. The *Overloaded* function
 - 2B. The *Ordered* function
 - 2C. The *Transmitted* function
3. The channel allocation to the ONU—the first OAM channel OAM_1 on the first wavelength channel λ_1 is assigned to the first ONU
4. **If** (Are all OAM channels served by the actual wavelength λ_j ?)
 5. **Then** The selection of the next wavelength λ_{j+1}
 6. **Else End If**
7. **If** (Can be the next ONU_{i+1} served by the last assigned OAM channel OAM_k ?)
 8. **Then** The calculation of the ONU delay $D_{ONU_{i+1}}$
 9. **Else** The new OAM channel OAM_{k+1} and the zero delay is assigned to the ONU_{i+1}
 - And** The calculation of the total wavelength delay D_{total}
10. **End If**
11. The bandwidth allocation of ONU requests $BR_{ONU_{i+1}}$ on the assigned OAM channel
12. The calculation of other result values
13. **If** (Are all ONU served?)
 14. **Then If** (Are there optional functions?)
 15. **Then** The selection of the optional function **And** Go to line 1
 16. **Else End If**
 17. **Else** Go to line 4
18. **End If**

Algorithm 6. The Dynamic Customized Allocation Method in the OAM&WDM-PON network

1. Loading of input parameters
 2. Customization of the requested bandwidth demands according to the SLA
 3. Functions for the auxiliary calculations
 - 3A. The *Overloaded* function
 - 3B. The *Ordered* function
 - 3C. The *Transmitted* function
 4. The channel allocation to the ONU—the first OAM channel OAM_1 on the first wavelength channel λ_1 is assigned to the first ONU
 5. **If** (Are all OAM channels served by the actual wavelength λ_j ?)
 6. **Then** The selection of the next wavelength λ_{j+1}
 7. **Else End If**
 8. **If** (Can be the next ONU_{*i*+1} served by the last assigned OAM channel OAM_k ?)
 9. **Then** The calculation of the ONU delay $D_{ONU_{i+1}}$
 10. **Else** The new OAM channel OAM_{k+1} and the zero delay is assigned to the ONU_{*i*+1}
 - And** The calculation of the total wavelength delay D_{total}
 11. **End If**
 12. The bandwidth allocation of ONU requests $BR_{ONU_{i+1}}$ on the assigned OAM channel
 13. The calculation of other result values
 14. **If** (Are all ONU served?)
 15. **Then If** (Are there optional functions?)
 16. **Then** The selection of the optional function **And** Go to line 1
 17. **Else End If**
 18. **Else** Go to line 5
 19. **End If**
-

In Table 3, output parameters of three allocation methods analyzed in the OAM&WDM-PON are summarized. It is obvious that cooperation of both operation technologies brings primarily marked and expressive possible WDM channel savings σ_{Ch-WDM} compared with allocation methods analyzed in the WDM-PON (see Table 1). It is noticeable that not only dynamic methods, but also the static method achieve high channel savings (96.30%, respectively, 85.19%). In the case of possible OAM channel savings σ_{Ch-OAM} , only the dynamic customized allocation method can achieve a non-zero value (25%) again. As can be seen, possible WDM channel savings are markedly higher than possible OAM channel savings for all considered allocation methods.

Table 3. Output parameters of allocation methods in the OAM&WDM-PON.

	Static	Dynamic	Dynamic Customized
A total number of utilized optical fibers N_{UtilOF}	1	1	1
A number of possible WDM channels per optical fiber $N_{Ch-WDMperOF}$	27	27	27
A number of possible OAM channels per wavelength $N_{Ch-WDMperW}$	4	4	4
A total number of utilized WDM channels $N_{UtilCh-WDM}$	4	1	1
A total number of utilized OAM channels $N_{UtilCh-OAM}$	16	4	3
A number of free WDM channels in the last optical fiber $N_{FreeCh-WDM}$	23	26	26

Table 3. Cont.

	Static	Dynamic	Dynamic Customized
A number of free OAM channels in the last optical fiber $N_{FreeCh-OAM}$	0	0	1
A number of active ONU units $N_{ONUactive}$	16	16	16
The efficiency of the WDM channel utilization η_{Ch-WDM}	14.81%	03.70%	03.70%
The possible WDM channel savings σ_{Ch-WDM}	85.19%	96.30%	96.30%
The efficiency of the OAM channel utilization η_{Ch-OAM}	100.00%	100.00%	75.00%
The possible OAM channel savings σ_{Ch-OAM}	0.00%	0.00%	25.00%

6. Discussion

For this work, it is essential to discuss obtained results in detail and simultaneously, to compare them with other studies and published works. First, an evaluation of acquired simulation results is introduced. Because a graphical presentation of all realized interpretations and evaluations of simulation results could lead to a massive extension of the contribution's volume, a comparison of channel utilization's efficiencies for proposed allocation methods is added in this section as an example. Then, a summary of obtained relevant findings is realized.

In Figure 3, a comparison of analyzed allocation methods is displayed for the efficiencies of WDM and OAM channel utilizations for utilized operating technologies. It is obvious that the static method has the highest channel utilization in all cases. The dynamic method can bring some channel saving only at the WDM channel allocation. The most prospective option seems to be a combination of WDM and OAM operating technologies. It achieves the lowest channel utilization in both WDM and OAM areas and can bring the highest possible channel savings thanks to this fact.

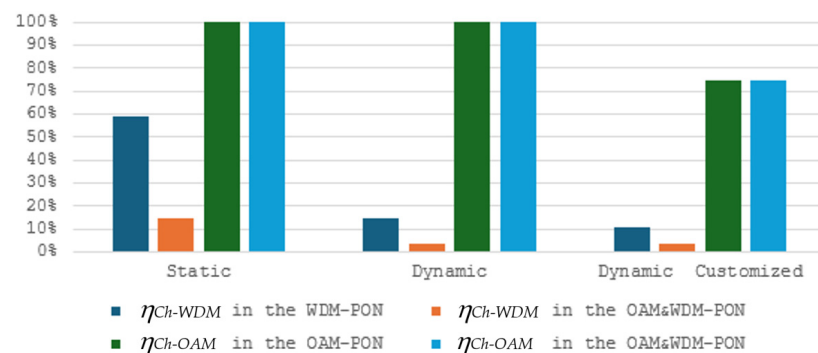


Figure 3. The comparison of efficiencies of the WDM and OAM channel utilization for three allocation methods for different operating technologies.

From the viewpoint of application in future OAM&WDM-PONs, resource efficiencies of the presented allocation methods are evaluated, and the following findings can be summarized:

- The static allocation methods do not save a number of utilized WDM channels nor utilized OAM channels.
- The dynamic allocation methods can save a number of utilized WDM channels but do not save a number of utilized OAM channels.
- The dynamic customized allocation methods save both a number of WDM and OAM channels. These methods are based on SLA values dedicated to the specific ONUs.

- WDM operating technology is more suitable than OAM operating technology due to the fact that the WDM provides more transmission channels than the OAM and more utilized optical fibers can be spared. The OAM/WDM combination seems to be the most suitable solution because it provides more transmission channels, and the number of optical fibers utilized can be rapidly decreased.
- The utilization of WDM and OAM channel allocation methods in a real network environment depends on numerous factors, for example, population density, network capital expenditures, and more.
- In the case of sparsely populated areas, static allocation methods for WDM or OAM operating technologies are preferable due to savings of capital and operational expenditures.
- In the case of densely populated areas, dynamic customized allocation methods based on SLA values utilized in the OAM/WDM combination bring savings of transmission channels in the utilized optical fiber, and in this way, savings of capital and operational expenditures can be achieved.
- The correct selection of WDM and OAM channel allocation methods depends on the requested aims of network operators.

The most related works are included in the State of the Art section, where each part is richly referenced to indicate that the applied research aim of this contribution is original and there are no known papers suitable for a near comparison in terms of the resource efficiencies in passive optical networks utilizing the hybrid OAM/WDM operating technologies. Therefore, other published works are taken into consideration, and a comparison of obtained results with other studies that appropriately refer to additional references is presented.

In [24], authors present tests of DBA algorithms in the XG-PON where no OAM and WDM operating technologies are considered. In [25], a real-time demonstration of the WDM-PON with the intention of latency and jitter is presented, where only fixed 25 Gbps interfaces are expected without OAM channels. A tutorial of traditional TDM-PON progress is processed in [26], where only the dynamic bandwidth allocation is included. In current ITU-T standards [27], it is supposed that the NG-PON2 system may contain a set of WDM channels. However, no OAN transmission channels are expected. Moreover, the issues associated with the dynamic assignment of wavelength channels are left to the implementor's discretion. Simultaneously, a bandwidth allocation within the individual channel with a single upstream line rate is based on the dynamic indication of ONU activities and their configured traffic contracts.

In [28], the bandwidth utilization and data transmission performance in the specific WDM-PON architecture are improved using AI (Artificial Intelligence) techniques. Another way for the wavelength allocation based on deep Q-learning is proposed in [29] for the WDM-PON. However, there is considered no OAM multiplexing together with real traffic loading in both cases. In [30], two different passive optical networks, WDM-PON and TDM-PON, are designed, optimized, and compared with each other for high-rate information communications. A comparative analysis of WDM-PON and TDM-PONs based on laboratory-based investigation in terms of their performance efficiency is also presented in [31]. Nevertheless, no wavelength and/or bandwidth allocation methods, together with the possibility of using the OAM channels in both works, are considered.

7. Conclusions

In this paper, we introduced a proposal for the novel OAM&WDM-PON architecture with a conventional point-to-multipoint topology and with the utilization of only passive optical splitters in remote nodes. For this proposed network architecture, novel static, dynamic, and dynamic customized allocation methods for effective utilization of network

resources can be considered and oriented on minimizing the number of working WDM and OAM channels that will be used for compliance with customers' requests for data transmitting in the proposed OAM&WDM-PON architecture.

For analysis of considered algorithms for allocation methods, a simulation model related to the proposed OAM&WDM-PON architecture with the P2MP topology is realized in the MATLAB programming environment. In this simulation model, various allocation methods for different operating technologies can be analyzed in detail. Then, acquired simulation results are evaluated particularly. Finally, appropriate efficiencies and possible savings of WDM and OAM channel utilization can be suitably compared.

Future Challenges and Research Directions

There can be considered many future challenges and ways of the research work extension that can be involved in the presented simulation model. Some of them are introduced here. Simulations can be extended to larger scales of ONUs and dynamic traffic patterns to strengthen the generality of findings. The SLA level can be defined as a number of nines as normally exploited by service providers. Input parameters of algorithms can be extended, and fiber lengths and a number of connectors influencing the total path attenuation can be involved. The available wavelength range can be divided into download and upload bands for more precise WDM channel allocation. Before selecting the appropriate operating technology, a selection of the appropriate network topology can be added. For comparing bandwidth allocation methods used in TDM technology, in the OAM/TDM combination or in the TDM/WDM combination, the addition of the TDM technology into the simulation model can be realized.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
BER	Bit Error Rate
CW	Continuous Wave
DM	Dimensional Multiplexing
DSP	Digital Signal Processing
DWA	Dynamic Wavelength Allocation
FMF	Few-Mode Fiber
FSO	Free Space Optics
GPON	Gigabit-capable Passive Optical Network
HSI	High-Speed Internet
IPTV	Internet Protocol Television
LG	Laguerre Gaussian

LP	Linearly Polarized
MDM	Mode Division Multiplexing
MIMO	Multiple Input Multiple Output
MMF	Multi-Mode Fiber
NG-PON2	Next-Generation Passive Optical Network 2
OAM	Orbital Angular Momentum
OBFB	Optical Bandpass Filter
OLT	Optical Line Terminal
ONU	Optical Network Unit
ONT	Optical Network Terminal
P2MP	Point-To-MultiPoint
PDM	Polarization Division Multiplexing
PON	Passive Optical Network
RN	Remote Node
SLA	Service Level Agreement
SLM	Spatial Light Modulator
SMF	Single-Mode Fiber
TDM	Time Division Multiplexing
VoBB	Voice over Broad Band
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch

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