

Simulation of Ring-based Passive Optical Network and Its Experimental Verification

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Abstract—Passive Optical Networks (PONs) are mostly used as modern high-speed access networks today. Typically, PONs are based mainly on tree or hybrid tree-star topologies in practice. However, these topologies are significantly vulnerable, especially in case of sophisticated attacks or global malfunctions of central optical line termination (OLT) units. Due to that, an innovative idea of forming PON with a simple ring topology by using standard passive splitters was proposed and is presented within this paper. Thanks to a ring topology, the secondary OLT unit can be placed in any potential location within the ring and this can significantly increase the vulnerability of the whole network. The article contains the description of this idea and also necessary simulations were performed. To verify these theoretical assumptions, experimental PON network with a ring topology was created and its characteristics were measured and compared with simulations and models. Moreover, the functionality of the protection mechanism was confirmed as well as the functionality of the entire ring PON network.

Index Terms—Passive optical network, protection, ring topology, splitters.

I. INTRODUCTION

Modern passive optical networks (PONs) represent a promising solution for future high-speed access networks providing shared transmission rates of 1, 2.5 or 10 Gbps for up to 256 connected users [1]. Typical PON consists of central optical line termination (OLT) unit, which connects the whole PON into backbone telecommunication systems and it also provides management and controlling functions, since it acts as a master unit [2]. Optical distribution network (ODN) represents necessary optical infrastructure and it contains only passive optical components such as optical fibres, connectors, splices, passive splitters or filters, etc. Optical network units (ONUs) or terminations (ONTs) are located at the end-users (subscribers) and they provide optical-electrical conversion as well as conversion of communication protocols to ensure the connection of subscribers into PON [1].

Nowadays, PONs are typically deployed for first-mile access networks to provide fast and reliable network connection mainly for households, offices and industry applications [1]. These applications are generally not very critical regarding the protection against network malfunctions. However, PONs can be also used for several specific applications [3] in industry, business, office or army sectors, which usually require higher level of protection together with the guarantee of maximum functionality of the whole network infrastructure. It is obvious that it is necessary to develop efficient protection and backup mechanisms to protect critical optical units in PONs as well as the whole optical distribution network. One of the most serious problems consists in a protection of OLT unit, which is a central optical unit of the whole PON. It is obvious that its potential failure or malfunction would surely result into a collapse of the whole PON. A typical optical distribution network usually has a star topology with a single branching point, or a tree topology with several branching points [1], which makes the methods for OLT backup difficult. While in case of a star or a tree topology all optical fibres are concentrated into one single central point, the secondary OLT can be placed only into the same place as the primary one. This OLT backup cannot be very reliable, since the whole infrastructure is still vulnerable in many situations, e.g. global power failure, floods, terrorist action, etc., because both OLT units (primary and secondary) can be disabled by a single sophisticated attack [4].

For that reason, the following innovative idea of forming a PON network with ring topology is proposed to protect critical applications of PON networks. The first proposals of ring topologies for PON were already introduced [5], [6], but they usually require special ONU units with optical switches and other nonstandard enhancements [7]. Nevertheless, a ring topology could be also easily formed by using standard passive optical splitters with symmetric or asymmetric splitting ratios, which would enable placing the backup (secondary) OLT unit at any position in a ring thus making the whole infrastructure less vulnerable. However, due to the high insertion loss of passive splitters causing high attenuation in case of a ring topology, this idea would not be very suitable for standard PON applications, but still it could be useful for well-protected specific situations and applications in local area networks [1].

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The problem with high insertion loss can be partially eliminated by using asymmetric passive splitters with optimum splitting ratios to balance the attenuation in the ring-based PON network. Thanks to that, more ONU units can be connected to provide more efficient solution. The initial idea of PON protection using ring topology was partially presented in [8] as well as the mathematical model for calculating optimum splitting ratios of used asymmetric splitters. Therefore, this idea was further extended and the simulations of transmission characteristics of ring-based PON were performed and are presented in this paper. Moreover, the experimental ring PON network was realized by using real equipment and asymmetric splitters, the protection mechanism verified and network parameters measured. Thanks to that, the comparisons between simulated and measured results are presented in this article as well as the verification of the functionality of proposed idea.

II. RING-BASED PON NETWORK

The ring topologies are usually used for backbone telecommunication networks (SDH, OTH, SONET), because they offer simple possibilities for efficient network protection. However, PONs are typically based on simple tree or star topologies, which represent the optimum scenarios for access networks. The PONs with bus topologies are not very typical, however, several potential applications for bus-type PONs have been already proposed [9]. Nevertheless, since the whole PON is controlled and operated from central OLT unit, its critical failure would certainly result in global PON collapse [1], [2]. Typical star or tree topologies usually offer only one possible location for both OLT units, because all optical fibres are concentrated only in a single point. Therefore, any sophisticated or global attack can easily disable both OLT units (primary and secondary) and this makes both topologies vulnerable. The ring topologies for PON were already presented, but only in case of WDM PON networks and hybrid WDM-TDM long reach PONs [6], or these solutions were based on special ONU units with optical switches and others nonstandard enhancements [5].

The concept of a ring-based PON presented in this article is based on using standard passive splitters with splitting ratios 1:2, which are connected to form a ring topology, as illustrated in Fig. 1. The main advantage of proposed ring-based PON is that it contains two independent OLT units, which can be placed at any potential location within the ring topology. The illustration in Fig. 1 assumes their location symmetrical on the opposite sides of the ring, but the whole infrastructure can be easily adapted to place both OLT units independently in the ring. In the initial state, the left half of a ring PON network containing ONU units no. 1, 2 and 3 is controlled and connected to OLT unit no. 1, while the second half with ONU units no. 4, 5 and 6 communicates with the OLT unit no. 2. However, since both halves of a ring are connected together to form a full ring topology, both halves can be operated by either OLT no. 1 or no. 2.

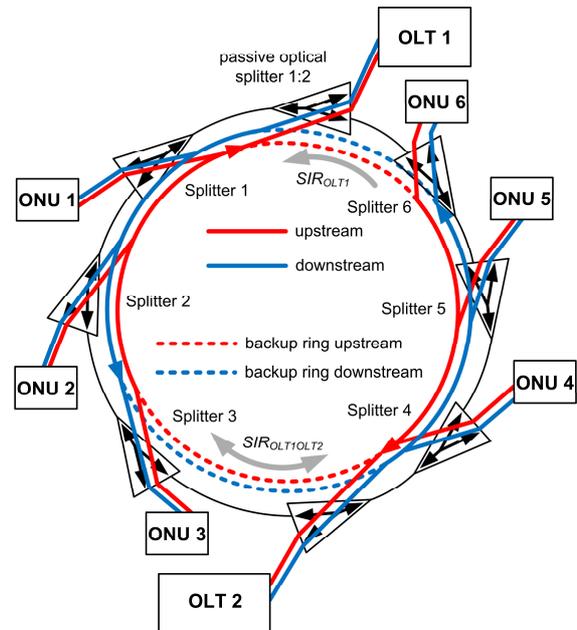


Fig. 1. The proposed idea of ring-based PON with both OLT 1 and OLT 2 units active.

This scenario with critical failure of OLT unit no. 1 is presented in Fig. 2.

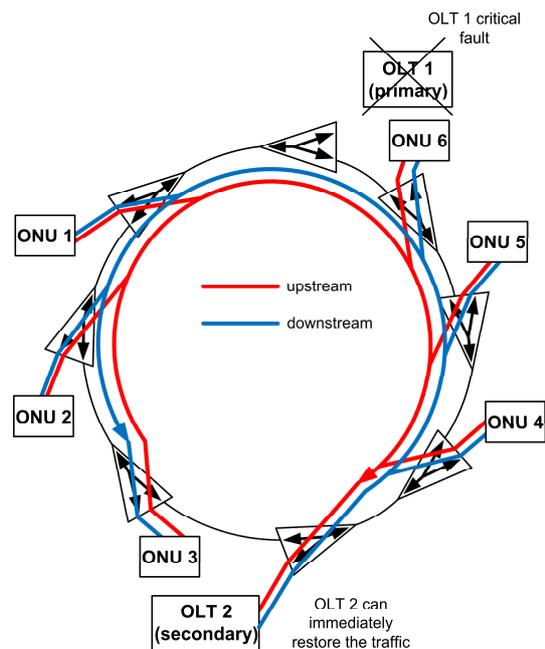


Fig. 2. The scenario with critical failure of OLT 1, when OLT unit no. 2 immediately restores the communication.

The important fact is that all ONU units can be easily switched between both OLT units in case of a failure of one of them without using any active switching unit. The traffic directions in a presented ring PON network can be easily adapted thanks to interconnections between both halves of a ring, which are illustrated as dashed lines in previous Fig. 1. It is obvious that the presented ring PON is basically composed of two bus-type networks with interconnecting fibres unused in initial state in Fig. 1, which are important when the communication directions are adapted, as illustrated in Fig. 2. Fig. 1 also contains looping optical SIR

(signal to interference ratio) signals propagating around the ring and passing through the backup (dashed) fibres between both halves of a ring. These optical signals can cause interferences with primary optical signals in both halves and can act as additional noises. Nevertheless, their optical power levels can be sufficiently attenuated due to passing all passive splitters and in case of optimizing their splitting ratios, these interfering signals can cause only minor increase of a noise.

Presented ring-based PON network can be based on symmetric passive splitters, but that scenario would result into very uneconomic solution. That is why an application of asymmetric splitters with calculated and optimized splitting ratios results into more optimum solution enabling maximum ONU units to be connected in a ring network. That is why it is necessary to perform detailed calculations and planning of the attenuation and optical power levels in all network nodes. The mathematical model for calculating optimum splitting ratios as well as resulting attenuations, optical levels and SIR values was presented in [8] and was used for designing following experimental ring-based PON network.

III. EXPERIMENTAL RING-BASED PON NETWORK

To verify previous ideas about the protection mechanism of proposed ring-based PON, the following experimental network was realized and also simulated. First, the mathematical model presented in [8] was used to calculate optimum splitting ratios of all asymmetric splitters used for forming the experimental network. However, only several asymmetric splitters with possible combinations of splitting ratios were available, therefore the designed ring PON network was optimized for using these specific splitters. The experimental network was based on the following optical components and equipment:

- 1) Huawei MA5603T multi-access platform containing H802GPBD OLT card with 2 OLT GPON modules using C class attenuation specification [10];
- 2) 6 pieces of Huawei EchoLife HG8010 GPON terminals used as ONU units;
- 3) EXFO FTB-500 platform containing FTB-5240S/BP module with optical spectrum analyser;
- 4) a set of asymmetric passive optical splitters with splitting ratios: 5%-95%, 10%-90%, 20%-80% and symmetric splitters 50%-50%;
- 5) two optical fibres with lengths of 5 km and characteristics according to the ITU-T G.652 D recommendation [11];
- 6) short optical patchcords with lengths of 2 or 5 meters with SC-APC connectors.

The OLT card used for the experimental ring PON network containing 2 OLT modules was based on the ITU-T GPON attenuation class C, therefore the interval of granted attenuation is $A_{max} = 30$ dB and $A_{min} = 15$ dB [10]. The recommendation also specifies the tolerable optical power levels for both upstream and downstream transmission directions in all network nodes. That is why the levels of optical signals were simulated and also measured and were compared with the values granted in proper recommendation. All optical fibres meet the ITU-T G.652 D specifications [11], therefore the attenuation coefficient used

for simulations was $\alpha = 0.4$ dB/km, the residual loss of all passive splitters was $A_r = 0.7$ dB and the insertion loss of SC-APC connectors was 0.2 dB. The ring PON network was designed by using asymmetric passive splitters with optimum splitting ratios, however, only a limited set of splitters with the most common splitting ratios was available. Therefore, the ring-based PON was designed to meet these criteria. Resulting PON network in the initial state with both OLT units active is presented in Fig. 3.

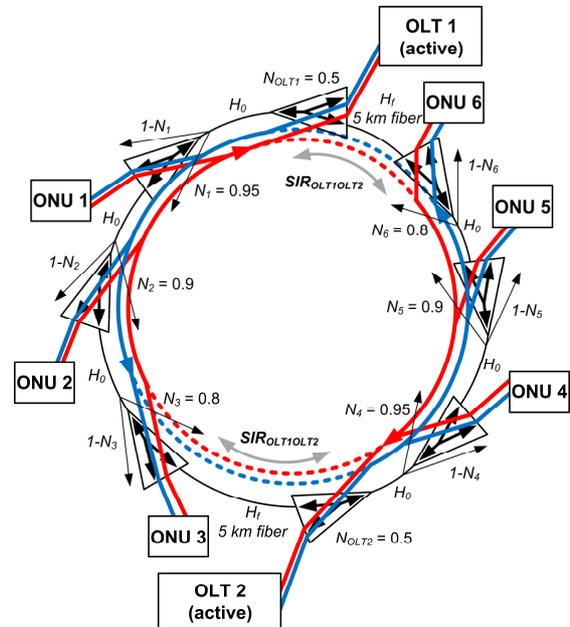


Fig. 3. The experimental ring-based PON network.

The transmission functions of asymmetric splitters are expressed as N_i , where i is the number of a splitter (position) in a ring. Obviously, both OLT units are connected via symmetric splitters (50%-50%) and the whole ring topology is symmetric, representing the most optimum solution, as it was described in [8]. The transmission functions of short optical patchcords are expressed as H_0 and transmission functions of fibres with the length of 5 km are H_f in the previous Fig. 3. Next, the functionality of projected PON network was simulated first followed by real measurements and experiments with real network. The functionality was tested during the simulations and measurements in 3 different scenarios – both OLT units active (normal status), only OLT unit no. 1 active (OLT no. 2 disabled due to its failure) and only OLT unit no. 2 active (OLT no. 1 disabled due to its failure). During these simulations and real experiments, the functionality of OLT backup mechanism was examined, the optical power levels in all network nodes measured and eye-diagram and Q-factor during simulations examined. The values and results obtained by simulations and real measurements were compared and are presented in the next section.

IV. SIMULATIONS AND MEASUREMENTS PERFORMED FOR EXPERIMENTAL RING PON NETWORK

A. Scenario with both OLT units Active

This situation is based on the initial state presented in Fig. 3, where both OLT units are active. The OLT unit no. 1

provides the communication with ONU units no. 1, 2 and 3, while OLT no. 2 is connected with ONU units no. 4, 5 and 6. First, the proposed ring-based PON network was simulated using RSoft OptSim™ optical simulator, especially the eye-diagrams in both upstream and downstream directions, Q-factors and optical power levels (Rx for received and Tx for transmitted optical power levels). The values of optical levels and Q-factors are presented in Table I, simulated eye-diagrams are shown in Fig. 4 for upstream and in Fig. 5 for downstream direction.

TABLE I. SIMULATED OPTICAL POWER LEVELS AND Q-FACTORS IN BOTH TRANSMISSION DIRECTIONS FOR A SCENARIO WITH BOTH OLT UNITS ACTIVE.

Path	Upstream @1310 nm			Downstream @1490 nm		
	Rx [dBm]	Tx [dBm]	Q-factor [dB]	Rx [dBm]	Tx [dBm]	Q-factor [dB]
1 st segment OLT 1 active						
OLT 1 – ONU 1	-15.56	3.06	29.37	-15.19	3.52	35.96
OLT 1 – ONU 2	-14.37	3.03	27.24	-13.14	3.52	37.28
OLT 1 – ONU 3	-12.85	3.08	36.97	-11.92	3.52	37.11
2 nd segment OLT 2 active						
OLT 2 – ONU 4	-15.56	3.06	29.37	-15.19	3.52	35.96
OLT 2 – ONU 5	-14.37	3.03	27.24	-13.14	3.52	37.28
OLT 2 – ONU 6	-12.85	3.08	36.97	-11.92	3.52	37.11

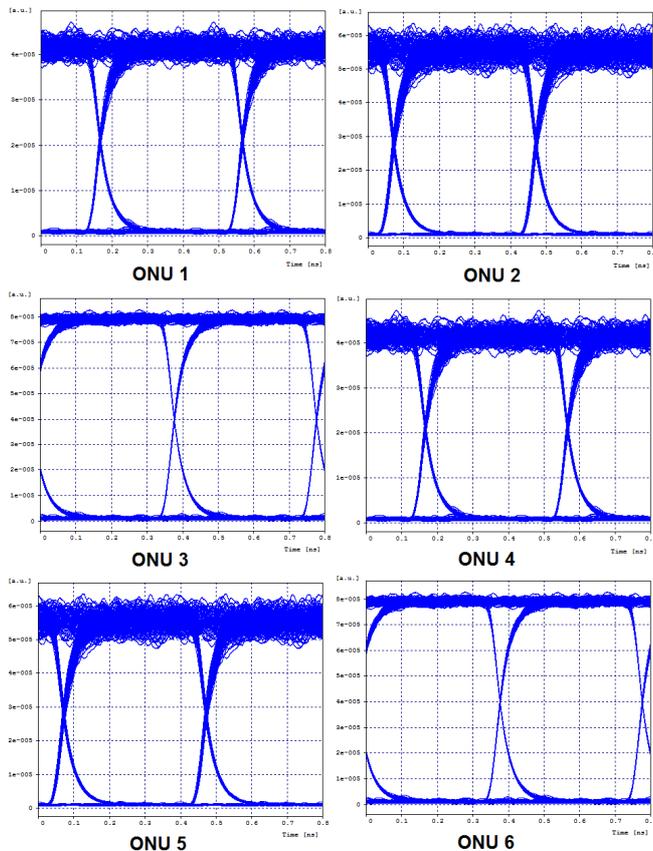


Fig. 4. The eye-diagrams for all ONU units in upstream direction.

It is evident that due to the symmetry of both halves of proposed ring network, the simulated transmission characteristics of ONU units in both halves are the same. The simulated optical power levels confirmed that the

designed ring PON network with asymmetric splitters according to the Fig. 3 meets the criteria of GPON attenuation class C. Moreover, the Q-factors and eye-diagrams illustrate that the proposed PON network is functional without any potential errors and problems. To verify these simulations, the ring-based PON network was realized, its characteristics measured and the functionality of the proposed backup mechanism tested. The following Table II contains the values of optical power levels measured by EXFO analyser and obtained by using Huawei internal monitoring system.

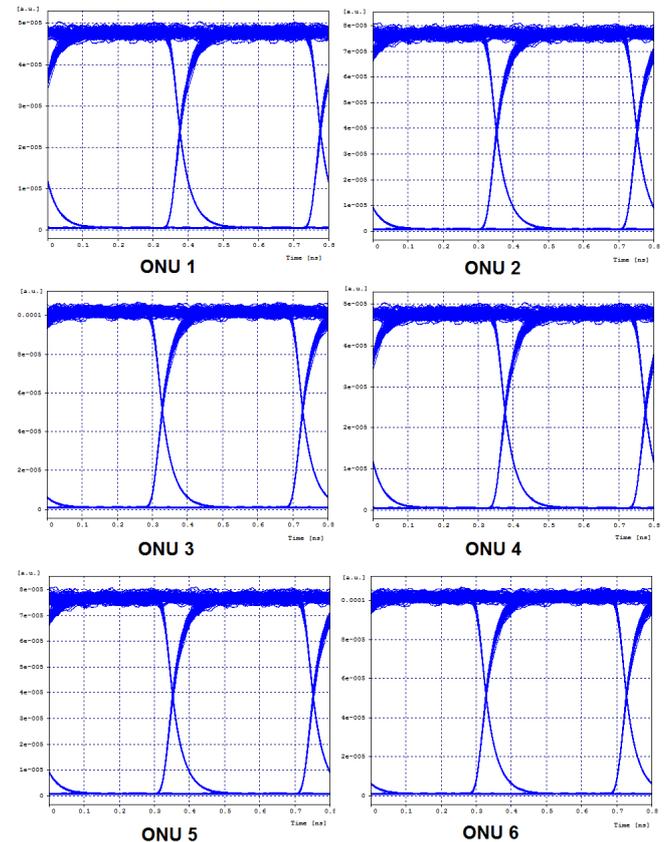


Fig. 5. The eye-diagrams for all ONU units in downstream direction.

TABLE II. MEASURED OPTICAL POWER LEVELS FOR REAL PON NETWORK IN BOTH TRANSMISSION DIRECTIONS FOR THE FIRST SCENARIO.

Path	Upstream @1310 nm		Downstream @1490 nm	
	Rx [dBm]	Tx [dBm]	Rx [dBm]	Tx [dBm]
1 st segment OLT 1 active				
OLT 1 – ONU 1	-15.58	3.22	-15.43	3.47
OLT 1 – ONU 2	-14.32	3.22	-13.15	3.47
OLT 1 – ONU 3	-12.77	2.83	-11.94	3.47
2 nd segment OLT 2 active				
OLT 2 – ONU 4	-15.50	2.65	-14.81	3.57
OLT 2 – ONU 5	-13.87	3.37	-12.97	3.57
OLT 2 – ONU 6	-12.63	2.65	-11.85	3.57

The results presented in Table II measured for real ring PON network are close to the simulated values from previous Table I, therefore the mathematical model and

simulations are accurate. Moreover, the experimental ring-based PON was fully operational in case that both OLT units were active.

B. Scenario with OLT no. 1 Active and no. 2 Disabled

Next simulation was performed for a situation, when OLT unit no. 2 was disabled and OLT no. 1 remained active. This should simulate the scenario with critical failure of OLT unit no. 2 and the whole ring PON network is connected only to OLT unit no. 1. The following Table III contains the results of simulated optical power levels and Q-factor for both transmission directions, while the eye-diagrams for upstream direction are presented in Fig. 6 and for downstream direction in Fig. 7 for this scenario.

TABLE III. SIMULATED OPTICAL POWER LEVELS AND Q-FACTORS WHEN OLT UNIT NO. 2 IS DISABLED AND OLT NO. 1 REMAINS ACTIVE.

Path	Upstream @1310 nm			Downstream @1490 nm		
	Rx [dBm]	Tx [dBm]	Q-factor [dB]	Rx [dBm]	Tx [dBm]	Q-factor [dB]
1 st segment OLT 1 active						
OLT 1 – ONU 1	-15.80	3.17	34.92	-15.64	3.52	40
OLT 1 – ONU 2	-13.94	3.15	34.85	-13.38	3.52	40
OLT 1 – ONU 3	-12.46	3.12	39.61	-12.26	3.52	40
2 nd segment OLT 2 disabled						
OLT 1 – ONU 4	-26.32	3.10	30.36	-26.13	3.52	32.86
OLT 1 – ONU 5	-24.83	3.12	33.23	-24.45	3.52	35.31
OLT 1 – ONU 6	-22.97	3.16	35.67	-22.41	3.52	36.32

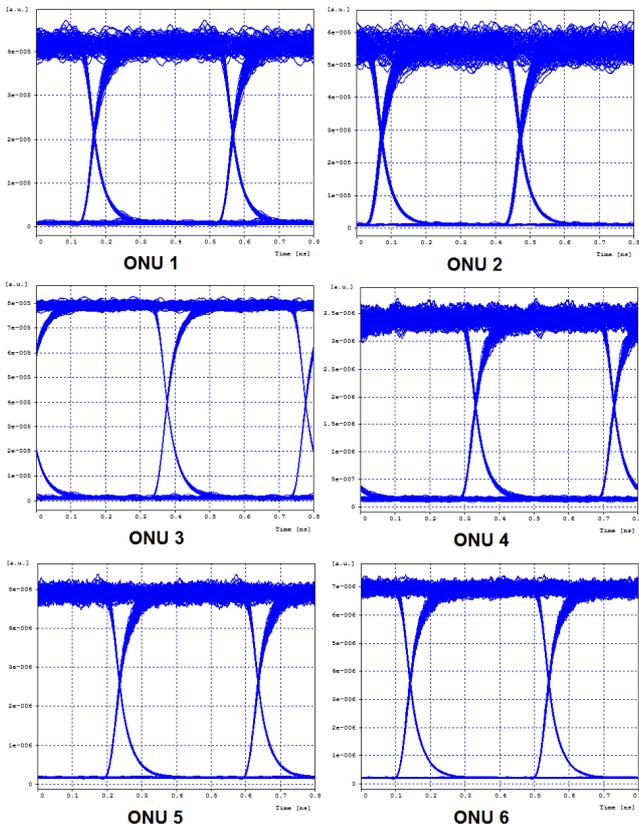


Fig. 6. The eye-diagrams for all ONU units in upstream direction.

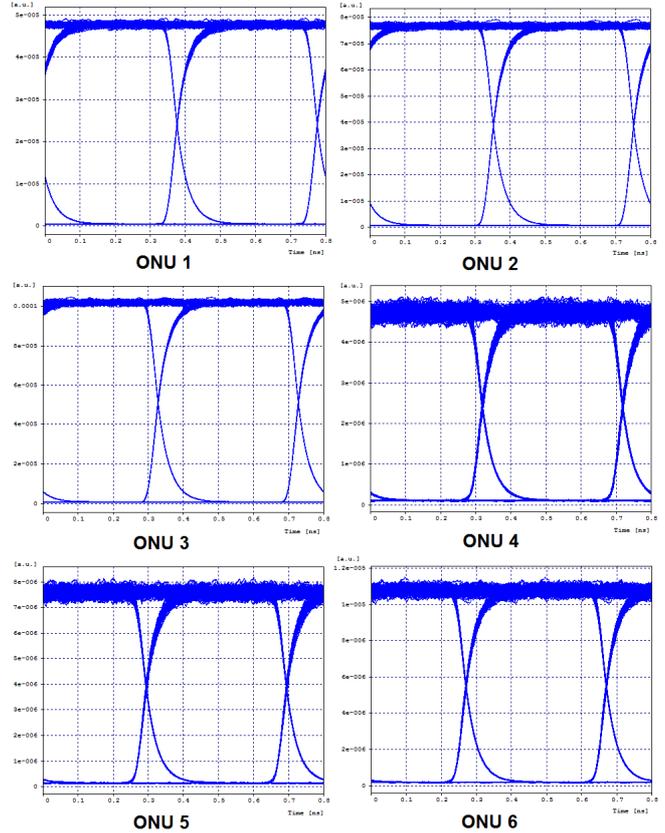


Fig. 7. The eye-diagrams for all ONU units in downstream direction.

Again, the simulations of Q-factor and eye-diagrams confirmed the functionality of all ONU units in ring-based PON network, moreover, all values of optical power levels meet the granted interval for GPON attenuation class C. To verify that the ring PON network is functional when OLT unit no. 2 was disabled, the experiment with designed real ring PON network was performed and the values of measured optical levels are presented in Table IV.

TABLE IV. MEASURED OPTICAL POWER LEVELS FOR REAL PON NETWORK IN BOTH TRANSMISSION DIRECTIONS FOR THE SECOND SCENARIO.

Path	Upstream @1310 nm		Downstream @1490 nm	
	Rx [dBm]	Tx [dBm]	Rx [dBm]	Tx [dBm]
1 st segment OLT 1 active				
OLT 1 – ONU 1	-16.23	2.78	-15.75	3.44
OLT 1 – ONU 2	-14.51	3.15	-13.09	3.44
OLT 1 – ONU 3	-12.92	3.15	-11.75	3.44
2 nd segment OLT 2 disabled				
OLT 1 – ONU 4	-26.51	3.15	-25.51	3.44
OLT 1 – ONU 5	-25.05	2.78	-23.69	3.44
OLT 1 – ONU 6	-23.32	3.15	-21.95	3.44

The practical experiment with real PON network verified the functionality of a ring protection mechanism. OLT unit no. 2 was disabled and as it was expected, the ONU units no. 4, 5 and 6 started to communicate with OLT unit no. 1, while ONU units no. 1, 2 and 3 remained connected to

OLTunit no. 1 as well. Thanks to that, the proposed ring mechanism can be used in practical PON applications to significantly improve their vulnerability against the malfunctions of central OLT units. All values of optical power levels measured for real ring PON network presented in previous Table IV meet the requirements for GPON class C. There are only some minor differences between measured and simulated values comparing Table III and Table IV.

C. Scenario with OLT no. 1 Disabled and no. 2 Active

This situation is similar to the previous scenario, nevertheless, this time the critical failure of OLT unit no. 1 is simulated, while OLT no. 2 is active. The simulations were performed again, however, according to the Fig. 3, the ring topology was designed symmetrical, and that is why the results of all simulations are the same as in the previous scenario with OLT no. 1 active and OLT no. 2 disabled. Therefore, the results for this third scenario can be obtained from previous Table III and Fig. 6 and 7 by substituting OLT unit no. 1 by OLT no. 2 and vice versa.

Nevertheless, the real experiment with real ring PON network for this scenario was performed to verify its functionality. Measured values of optical power levels are presented in Table V.

TABLE V. MEASURED OPTICAL POWER LEVELS FOR REAL PON NETWORK IN BOTH TRANSMISSION DIRECTIONS FOR THE THIRD SCENARIO.

Path	Upstream @1310 nm		Downstream @1490 nm	
	Rx [dBm]	Tx [dBm]	Rx [dBm]	Tx [dBm]
1 st segment OLT 1 disabled				
OLT 2 – ONU 1	-27.19	2.53	-25.51	3.57
OLT 2 – ONU 2	-25.72	2.21	-24.16	3.57
OLT 2 – ONU 3	-24.25	2.21	-22.37	3.57
2 nd segment OLT 2 active				
OLT 2 – ONU 4	-15.29	3.40	-14.72	3.57
OLT 2 – ONU 5	-13.06	3.40	-12.55	3.57
OLT 2 – ONU 6	-12.37	3.15	-11.62	3.57

This scenario was again fully functional and the communication between all ONU no. 1, 2, 3, 4, 5 and 6 and OLT unit no. 2 was successfully established. This situation confirmed that in case of OLT unit no. 1 critical failure, the OLT unit no. 2 can act as its backup and restore the functionality of the whole ring PON network.

V. CONCLUSIONS

This paper presented an innovative idea for protection of passive optical networks against the critical failures of central OLT units. The method is based on a ring topology, which can be easily formed by using standard passive splitters with splitting ratios 1:2 and no optical switches and other nonstandard active elements are necessary. The main advantage of proposed method is the relative independence of both primary and secondary OLT units, which can be placed at any possible location within the ring topology. However, the best solution is to design symmetrical ring

topology with both OLT units located at the opposite sides of a ring. Thanks to that, the PON network is less vulnerable, because in case of a failure of OLT unit in one of the halves of a ring, the second OLT can fully restore the functionality of a network. However, it is evident, that due to the high insertion loss of passive splitters, only a limited number of ONU units can be usually connected into the ring topology. Therefore, the proposed idea of ring-based PON network is useful especially for some critical applications, where maximum protection is necessary. It can be also applied for FTTx scenarios together with modern VDSL2 lines with FEXT cancellation techniques [12].

The correctness of proposed idea was also verified by extensive simulations and experiments with real ring PON network created by using real equipment. The simulations and measurements confirmed that the backup mechanism in a ring PON network is fully functional and in case of a primary OLT failure, the second OLT can restore the functionality of a network. The simulations and measurements also verified the mathematical model presented in [8], which was used for calculating the optimum splitting ratios of used asymmetric splitters and to design the whole infrastructure.

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