Application of Fiber Ring for Protection of Passive Optical Infrastructure

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Abstract. *Today, passive optical networks (PONs) are mostly used as modern high-speed access networks for various applications. However, there are also several specific applications, such as in business, office, army or science sector, which require a complex protection and backup system against failures and malfunctions. Typically, tree or star topologies are used for passive optical networks PONs. These topologies are vulnerable mainly against the failures of central optical line termination (OLT) unit. This paper presents an innovative method for protecting PONs by using ring topologies, especially the OLT unit. The method is described in the article, and an elementary mathematical model for calculations of asymmetric passive optical splitters together with an example is included as well.*

Keywords

Asymmetric optical splitter, passive optical network, protection, ring topology.

1. Introduction

The current generation of passive optical networks (PONs) is represented mainly by XG-PON, according to the ITU-T G.987 rec. [1], and 10GEPON presented in IEEE 802.3av [2]. These variants can offer a typical shared transmission speed of 10 Gbps for up to 128 connected optical network units (ONUs) for maximal distances 20 or 40 km. Today, PONs are mostly used as modern first-mile access networks to provide a fast and reliable network connection mainly for households, offices and industry [3]. The optical distribution network (ODN) has usually a star topology with a single branching point or a tree topology with several branching points. These applications are generally not very critical from the point of protection against network malfunctions or network services inaccessibility.

However, PONs can also be used for several specific applications in industry, business, office or army sectors, which usually require a higher level of protection and service availability together with the guarantee of a maximum functionality of the whole network infrastructure. It is obvious that it is necessary to develop advanced and efficient protection and backup mechanisms to protect critical optical units in PONs as well as in the whole optical distribution network. One of the most serious problems consists in the protection of optical line termination (OLT), which is the central optical unit of the whole PON. This unit provides mainly controlling, management and servicing of the whole network, and it also connects the PON network to the backbone telecommunication infrastructure [4]. Its potential failure or malfunction can result in a collapse of the whole PON.

A typical optical distribution network has a star topology with a single branching point, or a tree topology with several branching points [3], which makes OLT backup difficult. Because for star or tree topologies all optical fibers are concentrated into one single central point, the backup OLT can only be placed at the same position as the primary OLT. This type of OLT backup is not very reliable and the whole infrastructure is still vulnerable in many situations, e.g. global power failure, floods, terrorist attacks, damage to the feeder optical cable etc. The ring topology is the optimal topology for the critical application of PON [5].

The first proposals of ring topologies for PON were already introduced [6], [7], but they usually require special optical network units (ONUs) with optical switches and other nonstandard enhancements [8]. Nevertheless, a ring topology could also be 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, thanks to the passive splitters, it is evident that a ring topology in case of PON would probably suffer several disadvantages, mainly the problem with attenuation. Therefore, the ring topology would not be very suitable for standard PON applications, but it could be useful for well-protected specific situations and applications in local area networks.

The main problem of a PON with a ring topology is a high value of insertion loss of passive optical splitters. Therefore, forming an optical distribution network using only standard symmetric passive splitters would result in not very optimal and effective solution, because only a limited number of ONUs could be connected into such networks. However, using asymmetric passive optical splitters with splitting ratios calculated and optimized for specific scenarios, could significantly balance the attenuation in the whole infrastructure, thus enabling more ONUs to be connected.

This paper describes a PON with a ring topology consisting of two independent OLT units and passive optical splitters. The following part is focused on a mathematical derivation of elementary formulas and equations for calculating the optimized splitting ratios for two scenarios with asymmetric splitters. These splitters could be very useful for balancing the overall attenuation in a ring infrastructure. An example of results is included as well.

2. Forming PON with Ring Topology

Tree or star topologies are the most common ones for PON networks because they can be easily formed using passive optical splitters and they offer useful advantages, such as the number of connected ONUs and the possibility to simply add new ones. The PONs with bus topologies are not very typical; however, several potential applications for bus-type PONs have already been proposed [9]. Ring topologies for PONs were already presented, but only in case of WDM PON and hybrid WDM-TDM PON [10], or these solutions were based on special ONUs with optical switches and other nonstandard elements [11]. Several initial ideas of enhancing the protection of PONs were presented in the author's recent article [12]. The main advantage of this proposal is the possibility to place primary and secondary OLT units almost anywhere in the ring. Since the whole traffic and the network is controlled and operated from the central OLT unit, its failure would certainly result in a global PON malfunction [3].

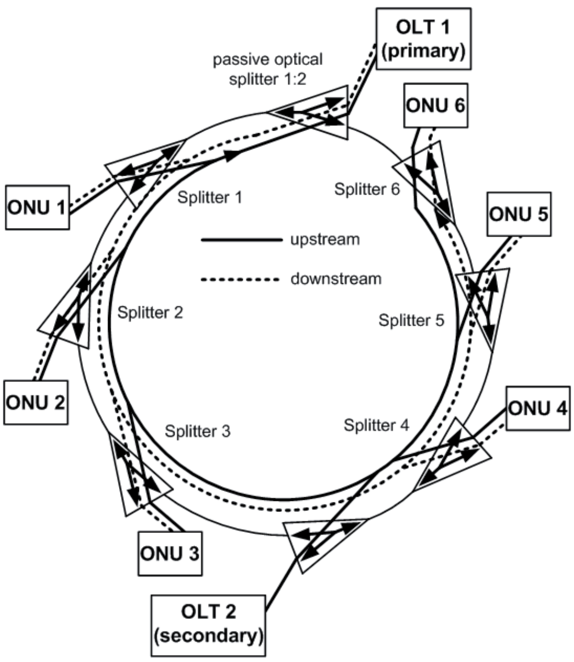

Fig. 1. The initial state of proposed ring-type PON.

A possible solution to easily form PON with ring-type topology is based on passive optical splitters with splitting ratios 1:2, which are connected to form a ring infrastructure. This solution is presented in Fig. 1. The infrastructure contains two independent OLT units, which can be placed at any location within the ring topology. The relative independence of both (or even more) OLTs locations is the main advantage of the proposed solution compared to standard tree or star topologies. While in case of a tree or star topology both OLT units (primary and secondary) can be broken with a single attack or a single global failure in one location. The OLTs in case of a ring topology are independent on each other and their elimination could be more difficult. All optical units (OLTs, ONUs) are connected via standard passive optical splitters with splitting ratios 1:2.

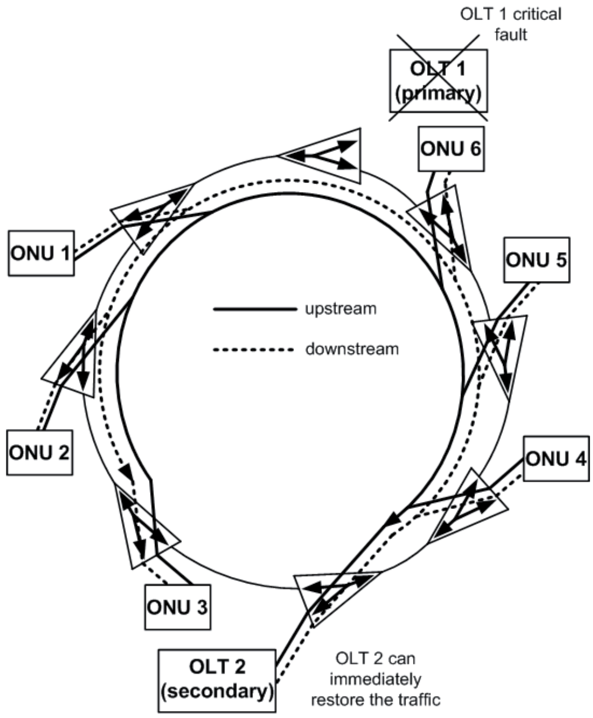

Fig. 2. Critical failure of the primary OLT unit.

In the initial state, the primary OLT (OLT 1) acts as the main OLT and provides all standard functions in the PON network, while the secondary OLT (OLT 2) is in a warm-state backup and only monitors the upstream traffic for detecting potential failures. Once a critical failure or a malfunction of the primary OLT occurs, the secondary OLT can switch immediately to the main role and it can take over the whole traffic. This situation is illustrated in Fig. 2.

The time delay necessary for switching the data traffic to the secondary OLT can be very short because the secondary OLT operates in a warm-state before the failure of the primary OLT. Comparing both Fig. 1 and 2, it is evident that both traffic directions can be easily adapted when the secondary OLT replaces the primary OLT. The presented ring topology is basically a bus type topology with unused interconnection between the last ONU and the first section of the ring (OLT unit). Therefore, it is necessary to perform detailed calculations and planning of attenuation and optical signal levels in all network nodes to prevent looping of forthcoming optical signals. The mathematical model and calculations of splitting ratios with resulting attenuations for all passive splitters as well as a practical example are presented in the following part of this article.

3. Mathematical Model of PON with Ring Topology

As shown in Fig. 1 and Fig. 2, there are two possible scenarios:

- Only the primary OLT 1 is active, while the secondary OLT 2 is in a warm-state backup and monitors passively the upstream traffic.
- Both OLT units are active, which means OLT 1 operates with ONU 1, ONU 2 and ONU 3 (according to Fig. 1) and OLT 2 ensures the communication with ONU 4, ONU 5 and ONU 6.

Both options are possible and will be evaluated further in the calculations. The initial calculation is based on the simplification that the formed ring infrastructure is symmetric, which means that both sides of the ring contain equal numbers of ONU units and both OLT units are placed exactly on the opposite sides of the ring. The calculation for a general ring-type PON could be slightly more difficult. The number of ONUs on each segment of the ring is M, which means that the number of passive optical splitters is M+1 because one optical splitter connects the OLT unit. Therefore, the overall number of ONU units in the whole ring network is $2M$ and the number of passive splitters is $2(M + 1)$.

The maximum attenuation in the whole PON network is defined as:

$$A_{\max} = L_{mT} - L_{mR\min} \text{ [dB; dBm, dBm]} \tag{1}$$

where the optical levels L_{mT} and L_{mRmin} are defined for transmitter power P_T and minimal receiver power P_R and are specified in the ITU-T recommendations or IEEE standards for each type of PON. The following calculations satisfy the condition that each receiver receives at least the optical power P_{Rmin}, which takes into account the specified power reserve. To simplify the calculation, the power reserve includes the attenuation of network branches and connectors, which connect the ONU units. Considering the attenuation of all optical fibers between two particular splitters A_0, which also contains the residual loss of one splitter and its connectors, the transmission function of each network element, H_0, between two splitters is defined as:

$$H_0 = 10^{-\frac{A_0}{10}} \text{ [-; dB]}. \tag{2}$$

The transmission function of each passive optical splitter is specified by its splitting ratio; therefore, the transmission function from the splitter's input towards its output is N_i, where index i indicates the number (position) of a splitter in the ring. Furthermore, since the sum of transmission functions of both splitters' outputs must be equal to 1, the transmission function of a splitter from its input towards the output with an ONU unit is 1 - N_i. The splitting ratio of each passive splitter has to be optimized to balance the optical signal into both outputs and to compensate the increasing loss of optical signal in case of distant ONU units. The optimal splitting ratio of both splitters, which connect the primary and secondary OLT units, is 50%:50%, which means that the transmission functions of these splitters, N_{OLT1}, N_{OLT2}, are expressed as:

$$N_{OLT1} = N_{OLT2} = 0.5\,. \tag{3}$$

The maximum attenuation towards the last ONU unit in the whole ring network needs to be checked to verify that it meets the requirements specified in (1). This overall attenuation $A'_{\max}$ also includes a reserve A_{res} for compensation of aging and temperature fluctuation of the attenuation of optical fibers. It is also necessary to consider the attenuation of splitter, which connects the OLT unit that means 50%:50% splitter reaches the attenuation of approx. 3.01 dB:

$$A'_{\max} = A_{\max} - A_{res} - 3.01 \text{ [dB; dB, dB, dB]}. \tag{4}$$

This condition can also be transformed into a transmission function:

$$H_{\min} = 10^{-\frac{A^i_{\max}}{10}} \text{ [-; dB]} \tag{5}$$

where $H_{\min}$ represents the transmission function satisfying the condition of minimum optical signal on the receiver (ONU with index i) side, and $A_{\max}$ with index i stands for the maximum overall attenuation of the path from the OLT towards the ONU unit with number i.

The optical level of signal passing throughout one of the ring segments from OLT 1 to OLT 2 is decreased by cascaded passive optical splitters and their transmission functions N_i as well as the attenuation of fibers. The transmission function of this segment of the ring can be thus expressed as:

$$H_{seg} = \frac{1}{2} H_0^{M+1} \prod_{i=1}^{M} N_i \tag{6}$$

where H_{seg} is the transmission function of the ring segment between OLT 1 and OLT 2, H_0 represents the transmission functions of fibers and connectors between splitters (the number of these elements is $M + 1$, where M is the number of ONUs in one segment of the ring topology) and is defined according to (2), N_i stands for the cascaded transmission functions of M passive optical splitters in the segment, and the term 0.5 represents the splitter 50%:50% connecting the OLT unit. The transmission function for the M ONUs connected in the second segment of a ring topology (after the optical signal passes the first segment of network) is based on the previous conclusions. The minimum transmission function (transmission function satisfying the condition of minimum receivable optical signal) for the first ONU unit (ONU 4 in Fig. 1) connected in the second segment of the ring topology can be thus derived as:

$$H_{\min} = H_{seg} H_0 \left(1 - N_4\right) \quad (7)$$

where H_{seg} and H_0 are the previously presented transmission functions, and $1 - N_4$ represents the transmission function of splitter no. 4 towards the ONU unit. The same minimum transmission function for ONU 5 can be expressed as:

$$H_{\min} = H_{seg} H_0^2 N_4 \left(1 - N_5\right). \quad (8)$$

Generally, the formula for calculating the minimum transmission function for the j^{th} ONU unit can be derived as:

$$H_{\min} = H_{seg} H_0^j \left(1 - N_j\right) \prod_{j=0}^{M-1} N_j \quad (9)$$

in which $N_0 = 1$. Equation (9) can be further improved by using (6):

$$H_{\min} = \frac{1}{2} H_0^{M+1} \prod_{i=1}^{M} N_i \cdot H_0^j \left(1 - N_j\right) \prod_{k=0}^{j-1} N_k \quad (10)$$

and finally as:

$$H_{\min} = \frac{1}{2} H_0^{M+1+j} \prod_{i=j}^{M} N_i \cdot \left(1 - N_j\right) \prod_{k=0}^{j-1} N_k^2. \quad (11)$$

Equation (11) represents the resulting general formula for calculating all transmission functions N_i and N_k of passive optical splitters in a ring topology to balance the overall attenuation and to connect a maximum number of ONU units based on the minimum receivable optical signal $H_{\min}$.

4. Calculation and Example of Results

The previously derived formulas were used for a practical application and calculation of a ring-type PON. This example proposes a ring PON network with 6 ONU units; therefore, each segment contains 3 units, so $M = 3$. The whole situation for both scenarios is illustrated in Fig. 3.

There are two possible scenarios, as illustrated in Fig. 3:

- Only the primary OLT 1 is active, while the secondary OLT 2 is in a warm-state backup and monitors passively the upstream traffic.
- Both OLT units are active, which means OLT 1 operates with ONU 1, ONU 2 and ONU 3 (according to Fig. 1) and OLT 2 ensures the communication with ONU 4, ONU 5 and ONU 6.

The PON is a GPON type class C; therefore, the maximum allowed attenuation $A_{\max} = 30$ dB. The splitters connecting OLT units are symmetrical (50%:50%) with attenuation of approx. 3 dB and the reserve for aging and temperature compensation is 1 dB. According to (3):

$$A'_{\max} = A_{\max} - A_{res} - 3.01 = 26 \text{ dB}.$$

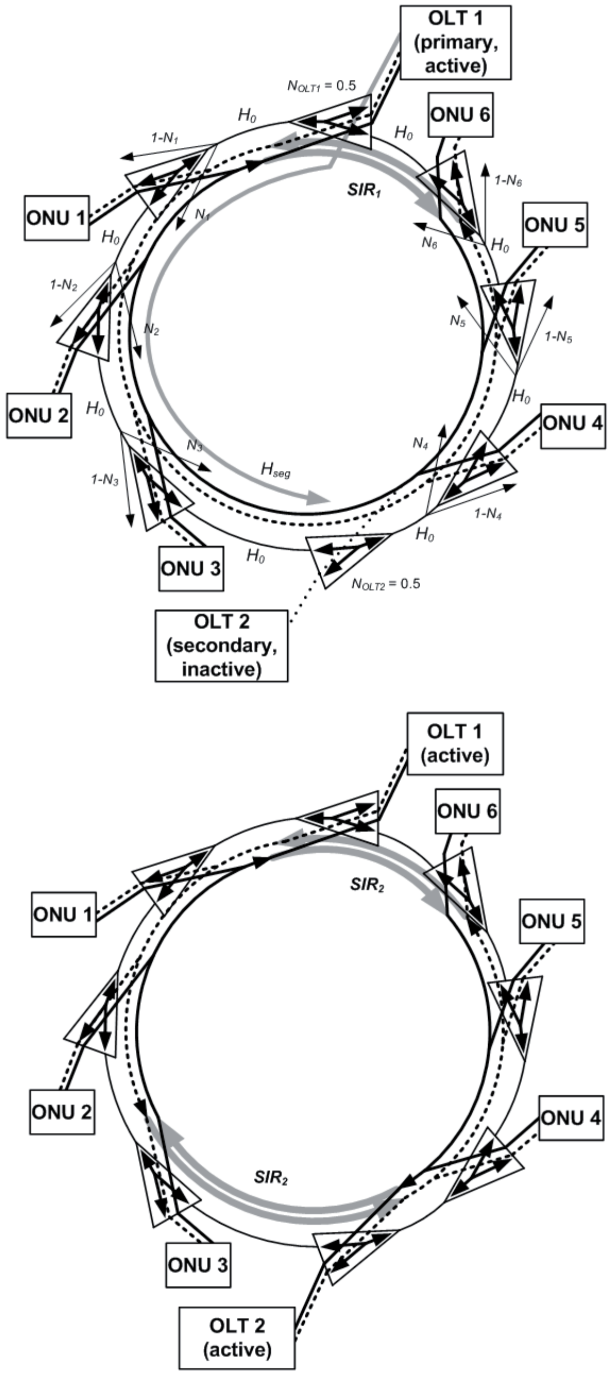

Fig. 3. Both scenarios with OLT units as well as relevant parameters used in the previous mathematical description.

The transmission functions, N_i (splitting ratios), of all passive splitters can be calculated using (11) and the resulting values in this example are:

$$N_1 = N_4 = 0.834; N_2 = N_5 = 0.752; N_3 = N_6 = 0.587.$$

The transmission functions of splitters toward the ONUs are given as 1 - N_i. The previous calculation illustrates that the most balanced and optimized PON ring network is symmetrical, which means that there are passive splitters in both segments of a ring topology with identical splitting ratios. However, the functionality of the designed ring PON network can be affected by looping optical signal propagation around the ring. The optical signal appears again at the beginning of the ring, thus causing primary optical signal interference. This attenuated and delayed optical signal acts as an additional noise interfering with the primary optical signal and increases the overall noise level in the ring. Nevertheless, the level of this disturbing optical signal can be sufficiently attenuated (thanks to passing throughout all splitters); resulting into only minor increase of noise detected in optical units. That is why the calculation of its level should be performed.

The first scenario assumes that the primary OLT 1 is active, while the secondary OLT 2 is in a warm-state backup and monitors passively the upstream traffic. In this case, the SIR (Signal to Interference Ratio) can be expressed as:

$$SIR_1 = \frac{2(1-N_M)}{H_0 N_M H_{\min}} \qquad (12)$$

where M is the number of ONU units in one segment of the ring network and N_M represents the transmission function of the passive splitter of the M-th ONU. The remaining parameters are presented in (5), (6). The value of the SIR parameter in this example is approx. 22.4 dB, which is fully suitable for the first scenario.

The second scenario of the ring PON network assumes that both OLT units are active, which means that OLT 1 operates with ONUs 1, 2 and 3 (see Fig. 1) and OLT 2 ensures the communication with OLTs 4, 5 and 6. In this scenario, the SIR parameter is derived as:

$$SIR_2 = \frac{1}{H_{seg}} = \frac{2}{H_0^{M+1} \prod_{i=1}^{M} N_i}. \qquad (13)$$

Its value for the previously presented example is approx. 12.2 dB, which is still marginally sufficient in case of 2-state amplitude keying used in PON networks. These results illustrate that the presented method of forming ring-type PON networks is applicable in practice and can be used for increasing the overall reliability and security of PON networks.

5. Conclusions

This article proposes an innovative method for the protection of passive optical networks, especially the central OLT unit. The method is based on a ring topology using passive optical splitters with splitting ratio 1:2, and neither special enhancement nor optical switches or routers are necessary. The main advantage of a ring topology is that both primary and secondary OLT units can be placed on the opposite sides of the ring, which could greatly increase the overall resistance of the whole network against critical failures, malfunctions or sophisticated attacks on its infrastructure. The PON with a ring topology is less vulnerable thanks to the secondary OLT, which can immediately restore the traffic if the primary OLT fails because it operates in a warm-state backup.

The second part of this article was focused on the mathematical derivation of an appropriate model for calculating and optimizing splitting ratios of used passive splitters. General formulas and conditions were presented as well as an example of their practical application. The example clearly illustrates that a PON with ring topology can possibly be used in practice and its parameters and characteristics can be balanced and optimized using previously presented formulas.

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