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Timing measurement and simulation of the activation process in gigabit passive optical networks

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The passive optical networks are widely used nowadays. Service providers have many customers in their distribution networks. The most important thing for communication between the end unit and the control unit is an establishment contact. Design and measurement of the activation process between optical network unit and optical line termination is presented. In general, the service providers have a big split ratio (up to 1:128) due to the connection eminent value of the customers per optical line termination port in chassis. We present the simulation of the connection process for 16, 32, 64, and 128 optical network units and the measurement for single optical network unit (the GPON Xpert is able to read a single connection process). We compare our results in simulation discussion.

Keywords: gigabit passive optical network (GPON), GPON transmission convergence (TC) layer measurement, transmission convergence (TC) layer simulation, Matlab, GPON timing.

1. Introduction

The bandwidth requirements are increasing every year from 20% to 30% due to the implementation of new services [1]. Nowadays, passive optical networks are widely developed. That is the reason why Internet services provider can increase the bandwidth for each customer. The connecting type according to fiber to the home/building (FTTH/B) dominated in Lithuania (from all European countries) in 2014 [2]. The situation is the same as foregoing in 2015. In general, FTTH Council does not take into consideration the technology for the customers. In Europe, gigabit passive optical network (GPON) is dominating, Ethernet passive optical network (EPON) is dominating in Asian access networks [3]. As was mentioned before, GPON is dominating for Europe networks thus we deal only with this technology. The description of GPON technology, timing relationship between optical line termination (OLT) and optical network units (ONUs), related works, simulation models, and measurement results are discussed in the following sections.

2. Related works

In recent years, many works related to GPON technology have been published. Works published up to date focus on a physical layer of GPON technology, especially line coding, dynamic bandwidth allocation (DBA) algorithm, end-to-end quality of services (QoS) and framing in a higher layer.

SMITH *et al*. [4] presented the packet delay variance and bandwidth allocation algorithms for extended-reach GPON. They proposed two algorithms for an extended distance optical distribution network (ODN). In general, the paper does not contain the timing scheduler for ONUs.

KYEONG-HWAN DOO *et al*. [5] dealt with a design of the retimed process for the long reach GPONs by an extender. The extender has been made with a field programmable gate array (FPGA). This solution probably could not be widely used due to a high price of the FPGA. On the other hand, the authors were able to use a split ratio up to 512 for a length 60 km of the distribution network.

SALIOU *et al*. [6] analysed an optical transport network based on time division multiplex (TDM) to aggregate multiple protocols (Ethernet, business services, node B, and GPON traffic). They needed to solve an issue with various traffic formats, especially for the GPONs where the traffic is transmitted via bursts. In general, the data sources were combined with the TDM technique into 10 Gbit/s stream.

Further, STEPNIAK *et al*. [7] introduced the bandwidth analysis of multimode fiber based PONs. They compared three architectures of the multimode PON numerically and experimentally. In general, the most important part of the PON is a splitter which may improve or decrease the bandwidth.

LEE *et al*. [8] dealt in with the extended reach GPONs with distributed Raman amplifiers. They were able to reach a distance of the distribution network up to 60 km by remote pumping. On the other hand, they had this distance limit because the distribution network length is limited by ITU. The main disadvantage of this solution is that the distribution network contains the active elements.

In our paper [9] we provided the simulation of the transmission convergence layer in the next generation PONs. We used the Matlab software for the simulation of 10 Gbit network numerical model. We simulated an equalization delay and influence of the refractive index on the timing.

MERCIAN *et al*. [10] dealt with report message scheduling in 1G/10G EPONs and GPONs, especially in upstream direction. Downstream direction was transferred by the broadcast method, therefore it was not necessary to solve this direction. The upstream direction in EPON and GPON is attended in the different mode. In general, it is not possible to compare these networks, because GPONs do not have carrier sense multiple access (CSMA) access method.

Further, ALSHAER and ALYAFEI [11] introduced an end-to-end QoS scheme for GPON. They used the dynamic weighted fair queuing for prioritizing of selected traffic. The authors had a solution for end-to-end QoS with *Report* messages.

YUANQIU LUO *et al*. [12] dealt with framing in GPON and NG-PON1. The authors compared the results for both standards. In general, they calculated only for framing but did not calculate all parameters in GPON and NG-PON1 networks. In both standards we need to count with round trip time (RTT), OLT response time, and relationship between OLT and ONU in a registering state.

We analyse the GPON technology and timing relationship between OLT and ONU in the next section.

3. Gigabit passive optical networks (GPONs)

GPON is a standard that offered sufficient bandwidth in the past. This standard was approved by ITU-T and has one important difference in comparison with older standards because GPON is able to use asynchronous transfer mode (ATM) and/or Ethernet protocols for data transmission. The general requirements of GPON are described in ITU-T G.984.1. In this document we can find the following information: specification of a split ratio, power budget, *etc*.

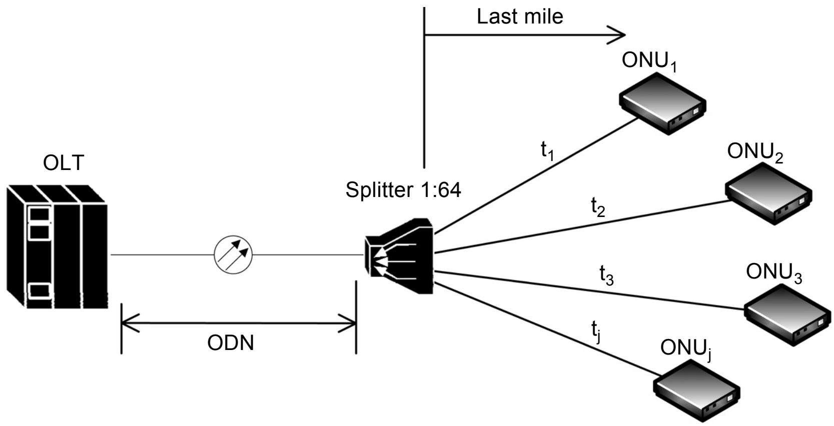

Fig. 1. The basic topology for GPON. OLT – optical line termination, ONU – optical network unit, ODN – optical distribution network, *t* – various times of propagation signal.

It can be seen from Fig. 1 that the times for a propagation signal from OLT to ONUs are different. This is the main point of our research. We focused on timing relation for control and end units for different split ratios. In other words, the initialization connection between these units is most important for the first establishing connection. Section 4 deals with connection establishment between OLT and first ONUs connected to the network.

In general, the most important physical layer requirements for our design and measurements are the maximum length of the distribution network of 20 km, split ratio at least 1:64 or higher, and attenuation classes.

For the GPON three attenuation plans were proposed: 5–20 dB, 10–25 dB, and 15–30 dB [13]. The limited length of the distribution network can be defined by the following equation:

$$l = \frac{A_c - F_l - S_{\text{loss}} - 0.5n}{F_a} \quad \text{[km]} \tag{1}$$

where A_c is the selected attenuation class [dB], F_l is the total loss of fiber in ODN [dB], S_{loss} is the splitter loss [dB], n represented the number of connectors, and F_a is the attenuation of used fiber [dB].

4. Communication between ONU and OLT units

The communication between ONU and OLT units is at first initialized by connecting ONU into the network. The OLT unit consecutively sends the downstream frames, which are exactly 125 μs long and contain physical synchronization block downstream (PSBd) header with *Psync* field of exact value used for ONU timing synchronization. The ONU, which is connected for the first time, needs to pass over the five states. The first state is the initial state (O1). In other words, the ONU needs to receive at least two frames with the same *Psync* value. In general, the initial state should be divided into three steps. At first, the ONU is in the hunt state, which means that the ONU is passive and receives the frames from the OLT. The parameters loss of signal/loss of frame (LOS/LOF) are set to 1. The ONU reads the incoming frames bit-by-bit and searches for the *Psync* field value. When this value is found, the ONU passes to the *Pre-Sync* state. At the same time the ONU sets the counter N_1 for correct incoming frames to 1 and waits for 125 μs, where the subsequent frame with the same *Psync* field value should occur. When another frame with correct *Psync* field is received, the counter N_1 is incremented and compared with the value M_1 which sets the number of subsequent correct frames to the transition of ONU into the synchronized state known as standby state (O2). The parameters LOS/LOF are cleared.

The ONU is now synchronized with the OLT in downstream direction but the subscriber still cannot transmit the data due to missing upstream synchronization. To obtain the upstream synchronization, the OLT unit periodically transfers the broadcast PLOAM message *Upstream Overhead* (PLOAM – physical layer operations, administrations and maintenance) which let the ONU configure the burst overhead fields for the subsequent upstream transmissions. The message is transferred three times and after the reception of at least one *Upstream Overhead* PLOAM message, the ONU sets the network parameters and move to serial number state (O3). The OLT unit then waits for 750 μs for ONU to process the message.

In the O3 state, the ONU starts TO1 (timer 1) with default value of 10 s where ONU waits for *Assign ONU-ID* message from the OLT. Meanwhile the OLT constructs a quiet window of 250 μs length by sending a broadcast frame with empty *BWmap* (in this configuration without the pre-assigned delay), which stops upstream traffic for all ONUs in the operation state to avoid collisions. The next frame from the OLT contains a *Serial Number Request* message addressed to Alloc-ID 0xFE (which is used for activation) with 13 byte grant (to send only a PLOAM message *Serial Number ONU*) and start time of 77 μs. After message reception on the ONU side, it waits for a locally random delay (0–48 μs) and when the start time is reached it sends a *Serial Number ONU* message. This message also contains the generated random delay. Note that prior to sending of the *Serial Number ONU* message, the ONU has to construct and send the PLOu (physical layer overhead upstream) header immediately before the *Serial Number ONU* message. While the OLT receives the *Serial Number ONU* messages from ONUs, it normally operates in the downstream direction for the next 2 frames. After that the OLT sends consecutively three *Assign ONU-ID* messages with a serial number obtained from the *Serial Number ONU* message from one ONU (the ONU is selected by OLT from the first incoming *Serial Number ONU* message). The serial number is a unique parameter for each ONU which identifies ONUs on the provider side. The *Assign ONU-ID* message sets the ONU-ID for direct addressing in the network and has to be received before the timer TO1 expires. Normally the timer TO1 expires only when more than 10 ONUs are trying to connect the line at the same time because the *Assign ONU-ID* message is applicable just for one ONU. If this message is sent periodically every 1 second, it allows 10 ONUs to be connected in 10 s and all the others will move back to standby state (O2). After targeted reception of at least one *Assign ONU-ID* message through a serial number, the ONU moves to ranging state (O4).

The ranging state (O4) is almost the same as serial number state (O3). The difference is in *Range Request* message which is sent directly to the specified ONU and in the absence of random delay because no collision can occur when only one ONU uses the line. The state O4 is the most important due to the setup of the equalization delay. The equalization delay synchronizes the communication of all ONUs in upstream direction. In other words, each ONU is in the unique distance from the OLT. With the equalization delay, the OLT keeps the synchronization of the time slots for the ONUs. The control unit can calculate the time equalization delay (Teqd) by the following equation [14]:

$$\begin{aligned}\mathrm{Teqd} &= T_{1490,\,i} + \mathrm{RspTime}_i + \mathrm{EqD}_i + T_{1310,\,i} = \\ &= T_{1490,\,i}\frac{n_{1310} + n_{1490}}{n_{1490}} + \mathrm{RspTime}_i + \mathrm{EqD}_i \qquad (2)\end{aligned}$$

where $\mathrm{RspTime}_i$ is the response time (μs), EqD_i is the estimation of the equalization delay for the fiber distance from the previous formula, n_{1310} represents the group velocity refractive index for 1310 nm in the ODN, n_{1490} represents the group velocity refractive index for 1490 nm in the ODN. The fraction with group velocities can be called the index correction factor. It can be expressed as [14]:

$$T_{1490,\,i} = (\text{Teqd} - \text{RspTime}_i - \text{EqD}_i)\frac{n_{1490}}{n_{1310} + n_{1490}} \tag{3}$$

The following equation defines the receiving time such as sum of the sending time and group velocity refractive index [14]:

$$\text{Trecv}_{N,\,i} = \text{Tsend}_{N,\,i} + T_{1490,\,i} \tag{4}$$

When we institute Eq. (2) and Eq. (3) into Eq. (4), the representation of the receiving time of the actual time instance can be obtained when GTC frame N is delivered to ONU_i [14]:

$$\begin{aligned}\text{Trecv}_{N,\,i} = {} & \text{Tsend}_{N,\,i} + \text{Teqd}\left[\frac{n_{1490}}{n_{1310} + n_{1490}}\right]_{\text{OLT}} + \\ & - (\text{EqD}_i + \text{RspTime}_i)\left[\frac{n_{1490}}{n_{1310} + n_{1490}}\right]_{\text{ONU}}\end{aligned} \tag{5}$$

The index factor should be written out with the following equation [14]:

$$\begin{aligned}\frac{n_{1490}}{n_{1310} + n_{1490}} &= \frac{n_{1490}}{2n_{1490} + (n_{1310} - n_{1490})} = \\ &= \frac{n}{2n + \Delta n} \approx \frac{2n^2 - n\Delta n}{4n^2} = \frac{1}{2} - \frac{\Delta n}{4n}\end{aligned} \tag{6}$$

For the partial derivatives with the variations of n and Δn, we have the following equations [14]:

$$\frac{\partial}{\partial n}\left(\frac{1}{2} - \frac{\Delta n}{4n}\right) = +\frac{\Delta n}{4n^2} \tag{7a}$$

$$\frac{\partial y}{\partial \Delta n}\left(\frac{1}{2} - \frac{\Delta n}{4n}\right) = -\frac{1}{4n} \tag{7b}$$

The above mentioned Eqs. (7) can be simplified as n is about 3 orders larger than Δn [14]. The previous expression is much smaller than the second one, and can be neglected. The second expression states that small changes in Δn will be translated into small changes of the index factor with proportion $1/4n$.

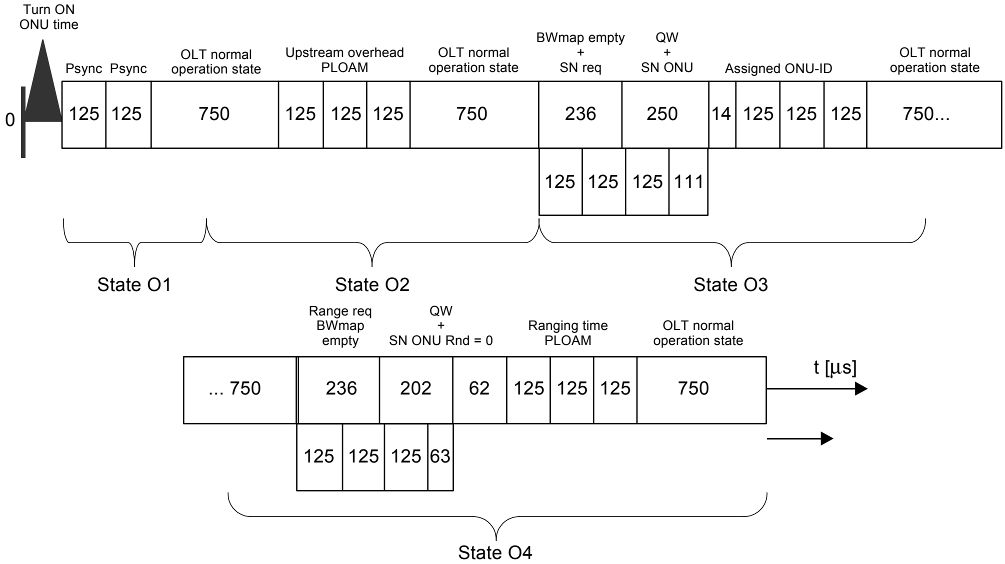

Fig. 2. Details of the ONU connecting into the passive network.

After receiving the *Serial Number ONU* message, the OLT side sends a *Ranging Time* message which contains the equalization delay for targeted ONU. This message is sent 3 times. Once the equalization delay has been negotiated, the ONU moves into the operation state (O5). The operation state is the final state for the ONU to transmit the data from the user to the network. The review of the mentioned states is shown in Fig. 2.

5. Simulation results

The variable nONU, which indicates a number of ONUs connecting to the network, is set to 16 from a possible range 1 to 128. Constant f_d means the frame duration which is exactly 125 µs. The timer TO1 is set to 10 seconds. Variable *curTime* is used as the real time counter and is set to 0 and the variable *delay* adds a time when the counter *curTime* overflows timer TO1. Variable ONUs holds an array of the ONU classes which contains Distance and Eqd attributes. The frame flow shown in Fig. 2 repeats every second. This setup also expects no pre-assigned delay used in an *Upstream Overhead* message from OLT and that the ONU will not send any additional data after a *Serial Number ONU* message. The value of M_1 in hunt state (O1) is set to 2. This means that only two consecutive frames with the correct *Psync* field value are needed for ONU to enter standby state (O2).

We selected the attenuation class B (10–25 dB). The simulation generates a random distance from OLT for all ONUs from the range 0 to 20 km. The next step calculates the propagation delay and adds the random delay from the range 0 to 48 µs for each ONU. The OLT holds the *Serial Number ONU* messages from all ONUs but due to the OLT configuration, it first responses by *Assign ONU-ID* message to ONU where the first *Serial Number ONU* message was received from. All other ONUs have to wait until the next *Assign ONU-ID* message with their serial number occurs. As shown in Fig. 2, this will happen right after 1 second so the variable *curTime* will be incremented by 1. The variable *curTime* is in each step compared with the value of the timer TO1 and if *curTime* overflows TO1 all unhandled ONUs will move back to standby state (O2) and the variable *delay* will be incremented by 1 because the next *Assign ONU-ID* message will not have a recipient. The equation for calculating activation time is:

$$t_a = \left[35 + 2\,\mathrm{ceil}\left(\frac{\mathrm{MRTD} + \mathrm{QW}}{f_d}\right)\right] + \mathrm{delay} + (i - 1) \qquad (8)$$

where ceil is the rounding function in Matlab, MRTD is the maximum round trip delay, QW is the quiet window length, f_d is the frame duration, delay is the counter of TO1 expirations and i is the cycle counter.

The simulations have been done by Mathworks Matlab tools and measurement with GPON Xpert professional device, which is designed for an analysis of the messages, frames, *etc*., at the transmission convergence layer and it has been developed by Tracespan. In our research we have two scenarios for the simulations and one for the measurement. The simulation scenarios use Eq. (8) and the process depicted in Fig. 2 for the calculation of the total times of each new connecting ONU to the PONs. Each ONU starts in the initial state (O1) and passes into the operational state (O5). The timer TO1 has the default value of 10 s and the distance of each ONU is generated from 0 to 20 km. The final results for 16 and 32 ONUs are depicted in Fig. 3 and for 64/128 ONUs – in Fig. 4. The maximum value of connecting activation time is around 32 s. The values seem random but they are not in order because the ONUs in the real

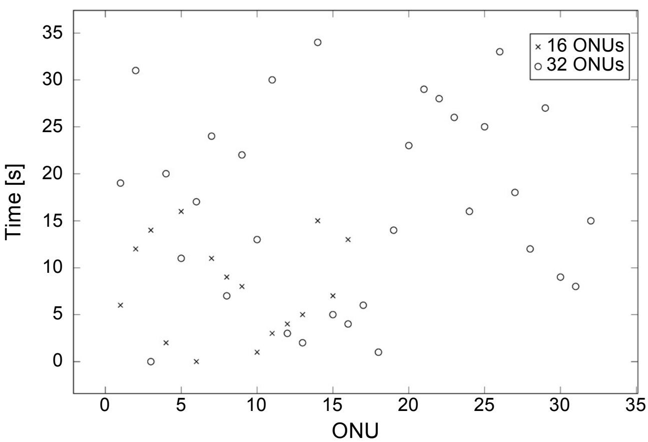

Fig. 3. Activation timing for 16/32 ONUs in the gigabit PON.

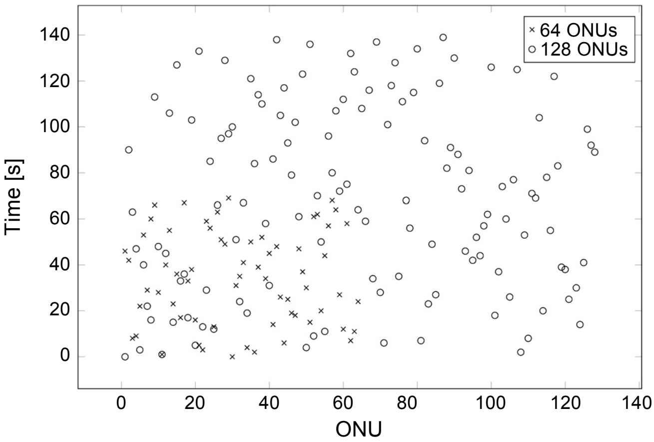

Fig. 4. Activation timing for 64/128 ONUs in the gigabit PON.

networks are in various distances from the OLT. When the timing is cogitated in the blackout, then the farthest ONU will be connected after 32 s. On the other hand, the real network has around thousands ONUs connected to the OLT. Currently, a higher number of CPU (central processor unit) is used for parallel calculation to reduce the activation timing.

6. Measurement results

The measurement topology is depicted in Fig. 5. The main difference is in the total insertion loss of the network caused by a splitter 1:4. For laboratory tests 64 ONUs

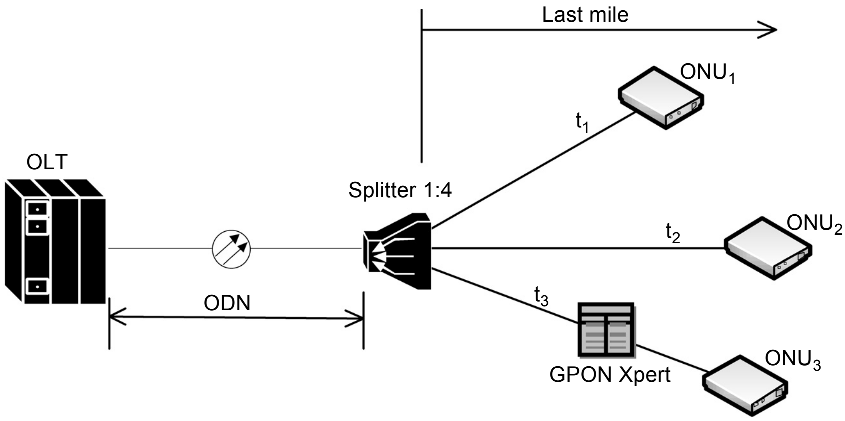

Fig. 5. The laboratory topology with GPON Xpert. OLT – optical line termination, ONU – optical network unit, ODN – optical distribution network, *t* – various times of propagation signal.

Table 1. Dying ONU process.

Line no.	Message no.	Time	ONU ID	Message type	Message source	Direction
1	1	00:00:04.364	1	Remote error indication	PLOAM message	Upstream
2	2	00:00:09.364	1	Remote error indication	PLOAM message	Upstream
3	3	00:00:14.365	1	Remote error indication	PLOAM message	Upstream
4	4	00:00:19.365	1	Remote error indication	PLOAM message	Upstream
5	5	00:00:24.364	1	Remote error indication	PLOAM message	Upstream
6	6	00:00:29.364	1	Remote error indication	PLOAM message	Upstream
7	7	00:00:31.933	1	Dying gasp	PLOAM message	Upstream
8	8	00:00:31.934	1	Dying gasp	PLOAM message	Upstream
9	9	00:00:31.935	1	Dying gasp	PLOAM message	Upstream
10	59	00:00:36.079	1	Deactivate ONU-ID	PLOAM message	Downstream
11	60	00:00:36.080	1	Deactivate ONU-ID	PLOAM message	Downstream
12	61	00:00:36.080	1	Deactivate ONU-ID	PLOAM message	Downstream

Table 2. ONU_3 activation process.

Line no.	Message no.	Time	ONU ID	Message type	Message source	Direction
1	117	00:01:41.508	Broadcast message	Assign ONU-ID	PLOAM message	Downstream
2	118	00:01:41.508	Broadcast message	Assign ONU-ID	PLOAM message	Downstream
3	119	00:01:41.508	Broadcast message	Assign ONU-ID	PLOAM message	Downstream
4	120	00:01:41.620	1	Ranging request	BWmap event	Downstream
5	1	00:01:41.621	1	Serial number ONU	PLOAM message	Upstream
6	121	00:01:41.731	1	Ranging request	BWmap event	Downstream
7	2	00:01:41.731	1	Serial number ONU	PLOAM message	Upstream
8	122	00:01:41.827	1	Ranging time	PLOAM message	Downstream
9	123	00:01:41.827	1	Ranging time	PLOAM message	Downstream
10	124	00:01:41.827	1	Ranging time	PLOAM message	Downstream
11	125	00:01:41.937	1	Request password	PLOAM message	Downstream

were not available. On the other hand, it is not important for our research because the GPON Xpert is able to read only one port of the splitter. The blackout scenario was simulated, and the control messages were captured with the unique device GPON Xpert. The measurement device can export results as html protocol. The GPON topology with GPON Xpert is shown in Fig. 5. The length of the ODN was 20 km and the attenuation class B was selected according to [13].

We measured two parameters: deactivation ONU with the blackout and complete activation process for ONU_3. In the deactivation state ONU was sent 3 types of messages: *Remote Error Indication*, *Dying Gasp*, and *Deactivate ONU-ID* (see Table 1).

It can be seen that the ONU after the blackout tries to connect with PLOAM message back to the OLT. This operation takes approximately 30 s and after this time the ONU sends the *Dying Gasp* message in the PLOAM part of the frame. The OLT answers with the *Deactivate ONU-ID* message to ONU. The process takes 36 s.

The second measurement deals with the analysis of the messages between OLT and ONU during the activation process. The simulation model represents the same progress as shown in Fig. 2. GPON Xpert is a complex device with many possibilities but it has one important disadvantage, the results for activation process show the time in milliseconds not microseconds. That is the reason why it is not possible to establish time more precisely. The ONU_3 is chosen for the analysis of activation process in our research, see Table 2.

GPON Xpert is not able to read the synchronization frames and *Upstream Overhead* messages. These messages are missing. In other words, the final time from Table 2 is quite different because some messages are missing. In general, our work proposes the complete activation processes with all the details. The last message *Request Password* means that the transmission in our laboratory topology was secured, but in default settings its value is set to 0 (unsecure). ONU_3 activation process takes 319 ms, without the synchronization frames transmission, *Upstream Overhead* messages, and quiet windows keeping.

7. Conclusion

Nowadays passive optical networks are widely used around the world. Gigabit networks are dominating. That is the reason why we dealt with the GPON standard. Internet services providers have in Europe many customers (up to 128) per single port in OLT. OLT has from 2 to 8 ports. In other words, each board in OLT chassis is able to attend up to 1024 customers. It means the high requirements for hardware claims for the blackout scenario (each ONUs has to reconnect back into PON).

Our simulation model has two scenarios. First, we simulated the reconnecting process of 16 and 32 ONUs. In other words, ONUs need to go over initial state (O1), standby state (O2), serial number state (O3), ranging state (O4), and operation state (O5). The operation state is the final state for our simulations, because ONU is able to transfer data simultaneously. We have successfully verified theoretical approaches by created simulation models. The correctness of the results has been verified by measurements. We achieved 17 and 34 s, respectively. On the other hand, the real network has several fold higher ONUs. The second scenario dealt with a higher split ratio of 64 and 128 ONUs. The results were 70 and 133 s, respectively. In general, OLT does not control only the connecting process but it needs to control the frame, data with higher priority, *etc*. We can calculate only 1 s per ONU for connection or blackout scenario from the simulations. Furthermore, we measured the connection time by GPON Xpert for dying ONU (leave ONU from ODN) and connection timing. If ONU leaves the ODN in conventional process, the total time is 36 s per single ONU. For the activation process of ONU we achieved the same results in comparison with the simulation 1 s per ONU.

The future research will continue with an implementation of our model into simulation software for optical networks, improving the activating time and the modification of the frame in GPON. In a single frame OLT is able to control only one ONU, this disadvantage eliminates the follow-up standard XG-PON [15].

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