Optimal techno-economic selection of the optical access network topologies

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Abstract - Optimal techno-economic selection of optical access network topologies involves finding the key techno-economic criteria that will be used for the topology selection. We have developed an analytical method for calculating optimal techno-economic selection of topologies. The proposed method determines the required number of optical fibers of certain characteristic segments of the access network, taking into account the density of users per 1 km^2, guaranteed bandwidth for each user, and the possible topology of optical access networks. The results show that the increase in density of users, with a constant guaranteed bandwidth, isn't the determining factor for the optimal choice of topology. On the other hand, the same results show that increasing the guaranteed bandwidth, with a constant density of users, represent critical elimination factor for optimal techno-economic selection of topologies. Under the same conditions, results show that the initially favorable topology, in terms of techno-economic feasibility, after a few iterations in bandwidth increase may become unfavorable compared to competing considered topologies.

I. Introduction

Authors involved in research related to finding the optimal choice of technologies and corresponding topologies for FTTx access networks usually start from the fact that the new network being built on the fiber optical cables basis or to perform the reconstruction of the existing copper network using method of shortening the copper wires. It often argues that the optical networks CAPEX, compared to solutions based on the shortening of copper pairs is still too high, because the share of construction costs which is dominant in relation to other costs [4] (Figure 1). Therefore it is proposed a gradual transition to FTTH solutions using xDSL technology.

The existing telecommunications infrastructure (cable ducts, pipes and sheathing of existing copper cables), which has previously invested huge capital, is often ignored or placed in another plan. Taking advantage of existing telecommunications infrastructure can significantly reduce construction costs and create favorable preconditions for investment in optical access networks as a better long term solution (Figure 2.). Figure 2 shows that the cost of cabling and fiber optic cables also have a significant share of CAPEX, and it would be desirable to minimize that part of the future investment.

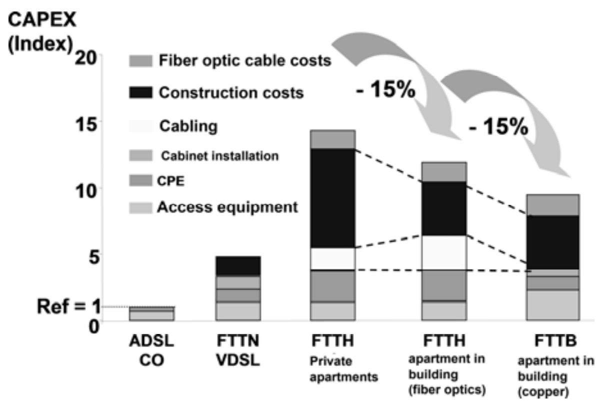


Figure 1. CAPEX comparison for FTTx solutions.

On the other hand, a lower number of required optical fibers imply a greater probability that the existing telecommunications infrastructure will be able to meet all present and future needs for expanding the capacity of the access network, caused by the increasing number of users or the guaranteed bandwidth to the user.

In this study we started with the thesis that there is a great probability that the increase in the number of users and the guaranteed bandwidth, initially favorable

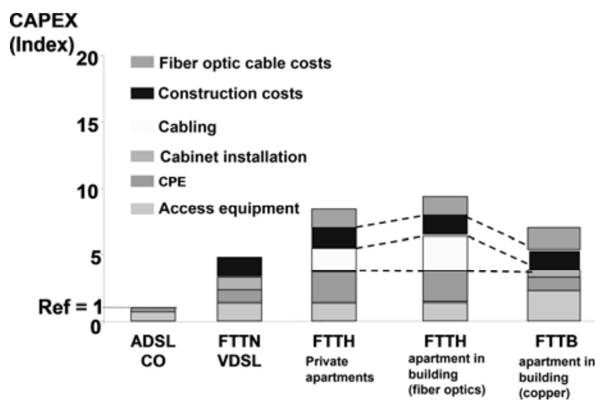


Figure 2. Comparison of reduced CAPEX for FTTx solutions.

technology, in terms of number and length of fiber optic strands, can turn into a very unfavorable and vice versa.

The first task of our research was to find those technical solutions of the FTTx access networks that maximum use the existing telecommunications infrastructure, in terms of permanent increase in the number of users, and guaranteed bandwidth for end users, in order to reduce construction costs, cabling and fiber optic cables.

The second task of the research was mathematical model, formed for the comparative analysis, which has to be technologically independent and relatively easy to use and understand.

In order to fulfill these tasks, we planned to check the behavior of available access technologies and associated topologies in terms of required number of optical fibers and their total length, in terms of increasing the number of users and guaranteed bandwidth.

Since the results for different technologies must be mutually comparable, telecommunications infrastructure and its topology has to be equal for all technologies.

For the purpose of analysis, we decided to use the users density as one of the influential parameters, rather than the number of users. We also decided that the density is uniform and that applies to an area of 1km^2. In this way it's possible to apply analytical calculation method and relatively simple mathematical model to demonstrate the increase in the number of optical fibers in accordance with the increasing density of users and the guaranteed bandwidth to the user. A detailed description of the mathematical model is presented in chapter two.

By applying the mathematical model we developed as well as analysis of the obtained results we have confirmed the starting hypothesis, but only in terms of increasing the guaranteed bandwidth, while in terms of increasing the users density it isn't confirmed. Some of the considered technologies and the corresponding topologies, by increasing the guaranteed bandwidth, have ceased to be the most suitable for the application and become unfavorable or very unfavorable. On the other hand, the initial schedule of technology under favorable condition doesn't change with increasing of users density. Comparing the areas with high and low status of benefits we have defined technologies and associated topologies which arises as the best candidates for further evaluation based on additional criteria, which was not the subject of this research, but the proposal for future research in this area. Other results and conclusions will be presented in detail in chapters III and IV.

II. Developing a Mathematical Model

A. *Initial assumptions*

Initial assumptions in defining the mathematical model are:

- Observed users are located within the squared area;
- Users in observed area are uniformly distributed that won't affect the universality of model, although they neglected their real grouping in the buildings as well as the number of building stories.
- Mathematical model treats a segment from central office (CO), through a central distribution cabinets (CDO) and distribution cabinets (DO) to the end user.

B. *Mathematical model*

If we look a part of an squared area of 1 km^2, where there are situated users with density g, the elementary area where there is only one user is given by expression:

$$P_e(g)=\frac{1}{g} \quad [m^2] \tag{1}$$

In this case area with N users is given by the following expression:

$$P_N(g)=N\cdot P_e(g) \quad [m^2] \tag{2}$$

Side of the square described with expression (2) is a following function:

$$a_N(g)=\sqrt{N\cdot P_e(g)}=\sqrt{\frac{N}{g}} \quad [m] \tag{3}$$

Assuming that the optical fibers distribution point to

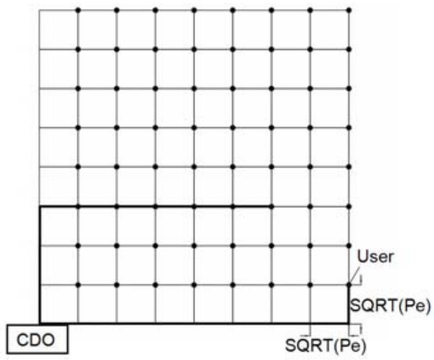


Figure 3. Distribution of the users on the imaginary surface of the observed square.

the users is on the edge of the square with surface area of $P_N(g)$, where is $N=1,2,3,\ldots$, assuming that each user is located on the edge of the square with surface area P_e (Figure 3), which doesn't lose the generality of the obtained solution, we obtain that the total length of optical fibers from the distribution point to each user (one fiber per user), represented by the following expression:

$$L_N(g)=\sqrt{P_e(g)}\sum_{i=1}^{\sqrt{N}}\sum_{j=1}^{\sqrt{N}}(j+i) \quad [m] \tag{4}$$

The expression (4) applies when the $\sqrt{N}$ is whole number and otherwise we are using the following expression:

$$L_N(g) = 2 \cdot \sqrt{P_e(g)} \sum_{i=1}^{\sqrt{\frac{N}{2}}} \sum_{j=1}^{\sqrt{\frac{N}{2}}} (j+i) \quad [m] \tag{5}$$

where $L_N(g)$ function gives a total length of optical fiber from optical fibers distribution point to N end users, as a function of the density of users

For cases of optical fibers distribution, into CDO or DO, active or passive network elements (*splitters*), in accordance with $1:2^i$, where i = 1, 2, 3, ..., n, expressions (4) and (5) are translated in the following form:

$$L_N(g) = \sqrt{P_e(g)} \sum_{i=1}^{M} \sum_{j=1}^{M} (j+i) \quad [m] \tag{6}$$

and

$$L_N(g) = 2 \cdot \sqrt{P_e(g)} \sum_{i=1}^{M} \sum_{j=1}^{M} (j+i) \quad [m] \tag{7}$$

where the variable $M = \sqrt{N}$ *and* $M = ROUNDUP\sqrt{N}$ (function ROUNDUP (x) is the rounding of the variable *x* to the first integer greater value), respectively, causing a minor mistake which is negligible.

If a technical solution of the access network predicts, except CDO, the existence of a number of DOs, which is closer to end users and their groups, then the expressions (4), (5), (6) and (7) refers to the access network part from DO to the end users. In this case, the optical fibers total length from DO to the end users, for a single CDO which is powered by the N users, we get by using the following expression:

$$L_{N(1:D)}(g) = \sum_{i=1}^{n} L_{N\,i}(g) = \begin{bmatrix} za\ N_i = N_{DO} \\ gdje\ je \\ i = 1,2,3...n \end{bmatrix} = \\ = N_{DO} \cdot L_N(g) \quad [m] \tag{8}$$

where n represents the number of DO within the area covered by a single CDO, and $L_{N\,i}(g)$ refers a total length of optical fibers from the i-th DO to end users.

$L_{N(1:D)}(g)$ represents the total length of optical fibers from all DOs to the end users within the area covered by the CDO.

We have assumed that each DO is situated on the further lower corner of square, compared to the CDO, and that these squares represent the total surface area of P_e, covered by single DO.

Based on such adopted assumption, the additional optical fibers length from the CDO to the all DOs, for the idealized topologies, which depends on guaranteed bandwidth to the end user and the user density, where $\sqrt{\frac{N_{\max}}{N_{DO}}}$ is an integer and $N_{\max} \neq N_{DO}$ and $N_{DO} \neq 1$, and splitter type *1:2*^{n}, n = 0, 1, 2, ..., represent a function given by the following expression:

$$L_{di}(B_G, g) = \left(2 \cdot \sqrt{\frac{N_{\max} \cdot P_e(g)}{N_{DO}}} \cdot \sum_{i=0}^{\sqrt{\frac{N_{DO}}{2}}-1} \sum_{j=1}^{\sqrt{\frac{N_{DO}}{2}}} (j+i) \right) \left(N_{DO} + \operatorname{sgn}(K(B_G)) \cdot \sum_{i=0}^{K(B_G)-1} 2^i \cdot N_{DO} \right) = \\ = \left(2 \cdot \sqrt{N_{\max} \cdot N_{DO} \cdot P_e(g)} \cdot \sum_{i=0}^{\sqrt{\frac{N_{DO}}{2}}-1} \sum_{j=1}^{\sqrt{\frac{N_{DO}}{2}}} (j+i) \right) \left(1 + \operatorname{sgn}(K(B_G)) \cdot \sum_{i=0}^{K(B_G)-1} 2^i \right) \quad [m] \tag{9}$$

When $\sqrt{\frac{N_{\max}}{N_{DO}}}$ isn't an integer, under the same conditions, then we used the following expression:

$$L_{di}(B_G, g) = \left[\sqrt{\frac{N_{\max} \cdot P_e(g)}{2 \cdot N_{DO}}} \cdot \left(-\frac{N_{DO}}{2} + \sum_{i=0}^{\sqrt{N_{DO}}-1} \sum_{j=1}^{\sqrt{N_{DO}}} (j+i) \right) \right] \left(N_{DO} + \operatorname{sgn}(K(B_G)) \cdot \sum_{i=0}^{K(B_G)-1} 2^i \cdot N_{DO} \right) = \\ = \left[\sqrt{\frac{N_{\max} \cdot N_{DO} \cdot P_e(g)}{2}} \cdot \left(-\frac{N_{DO}}{2} + \sum_{i=0}^{\sqrt{N_{DO}}-1} \sum_{j=1}^{\sqrt{N_{DO}}} (j+i) \right) \right] \left(1 + \operatorname{sgn}(K(B_G)) \cdot \sum_{i=0}^{K(B_G)-1} 2^i \right) \quad [m] \tag{10}$$

where N_{DO} represents the number of DO, and N_D is a number of splittings in each DO, or number of users that is powered by this DO. $K(B_G)$ is a function which represents the ratio of users guaranteed bandwidth B_G and the maximum guaranteed bandwidth, which in the considered topology requires no additional optical fibers between the CDO and DO, and depends on the number of distribution cabinets N_{DO}. The function $K(B_G)$ is given by the following expression:

$$K(B_G) = \begin{cases} 0 & , za \ \dfrac{B_G}{\left(\dfrac{B_{\max}}{N_{D\max}}\right) \cdot N_{DO}} \le 1 \\ \ln\left(\dfrac{B_G}{\left(\dfrac{B_{\max}}{N_{D\max}}\right) \cdot N_{DO}} \right) & , za \ \dfrac{B_G}{\left(\dfrac{B_{\max}}{N_{D\max}}\right) \cdot N_{DO}} > 1 \end{cases} \tag{11}$$

where B_{max} is the maximum bandwidth of one OLT module, and $N_{D\ max}$ is a maximum possible number of dividing the signal from one OLT module. On the other hand $B_G = B_{G\min} \cdot 2^i \quad [Mb/s]$, and i = 0, 1, 2, 3, ..., n, where n is the largest number such that the $\frac{N_{\max}}{2^n}$ is odd number or equal to one.

In expressions (9) and (10) square roots $\sqrt{\frac{N_{\max} \cdot P_e(g)}{N_{DO}}}$ and $\sqrt{\frac{N_{\max} \cdot P_e(g)}{2 \cdot N_{DO}}}$, respectively, determine the length of the side of the square whose area equals the surface occupied by a single DO, on the total area covered by a single CDO. The second bracket in expressions (9) and (10) determines the number of optical fibers depend on increasing of the guaranteed bandwidth B_G.

The total length of optical fiber from the CDO to the end user, depending on the guaranteed bandwidth on the end users side and the users density, for the idealized topology, is given by the formula:

$$L_{UKi}(B_G, g) = L_{N(1:D)}(g) + L_{di\,(1:D)}(B_G, g) \quad [m] \tag{12}$$

Mathematical model for nonidealized (real) topologies (topologies with real users distribution) is derived from the mathematical model for the idealized topology, which is described in terms from (1) to (12). It doesn't mean that the idealized topologies can be used in real topologies, but they are less possible in practice.

Part of the mathematical model described in expressions from (1) to (8) is universal and applies to nonidealized topologies, except in terms of the real users distribution, because it assumes a uniform users distribution. The reason is that in this segment (from the point of the last splitting of the signal to the end user), all users have their own fiber, which isn't shared with other users, and this segment is independent of the increase of user guaranteed bandwidth.

The modified expression for nonidealized topologies is given by relation:

$$L_{dn\,(1:D)\,i\,(i+1)}(B_G, g) = L_{di\,(1:D)\,i\,(i+1)}(B_G, g) \cdot \frac{D \cdot N_{(1:D)\,i\,(i+1)}}{N_{D\max}} \quad [m] \tag{13}$$

where $L_{dn\,(1:D)\,i\,(i+1)}(B_G, g)$ is a function that gives a total additional length of optical fibers between the *i*-th and $i+1$ splitting level, depending on the guaranteed bandwidth B_G and user density *g*, for the nonidealized topology. $N_{(1:D)\,i\,(i+1)}$ is the splitters number *1:D* in nonidealized topology, on the $i+1$ level of splitting. *D* is the maximum possible number of users behind the observed DO.

In equation (13) factor $\frac{N_{D\max}}{D}$ determines how much is the maximum possible number of splitters with splitting ratio of 1: D in idealized topology, between the first and second splitting levels. By dividing $L_{di\,(1:D)\,i\,(i+1)}(B_G, g)$ with this ratio and multiplying by the number $N_{(1:D)\,i\,(i+1)}$, we get the total increase in length of optical fibers between the *i*-th and $i+1$ splitting level for all splitters with splitting ratio of *1:D*.

The total length of optical fibers in no idealized topology, depending on the guaranteed bandwidth for end users and the users' density, we get by using the following formula:

$$L_{UKn}(B_G, g) = L_{N(1:D)} + \sum_{i=1}^{2} \sum_{\substack{k=2 \\ k\in\{2,3,4,6,8,12,16,24,32,48,64,128,\ldots,D_{\max}\}}}^{D_{\max}} L_{dn\,(1:k)\,i\,(i+1)}(B_G, g) \quad [m] \tag{14}$$

where $L_{N\ (1:D)}$ is given by the expression (8), and $L_{dn\,(1:k)\,ij}(B_G, g)$ is given by the expression (13). In equation (14), in the first sum, *i* represents splitting ratio. The second sum determines the presence of the splitter with splitting ratio *(1:k)*, where $k \in \{2, 3, 4, 6, 8, 12, 16, 24, 32, 48, 64, \ldots, D_{\max}\}$.

The total length of optical fibers from the CO to the CDO, which depends on the distance from the CO to the CDO and guaranteed bandwidth, is given by the following expression:

$$L_{CO-CDO}(B_G, l) = \sum_{i=1}^{N_{OLT}} \frac{B_{G\,i}}{\left(\frac{B_{\max}}{N_{\max}}\right)} \cdot l_i = \begin{bmatrix} ako\ je \\ B_{G\,i} = B_G \\ za\ \forall\ i\ gdje\ je \\ i = 1, 2, \ldots, N_{OLT} \\ tada\ slijedi\ da\ je \end{bmatrix} = \frac{B_G}{\left(\frac{B_{\max}}{N_{\max}}\right)} \sum_{i=1}^{N_{OLT}} l_i \quad [m] \tag{15}$$

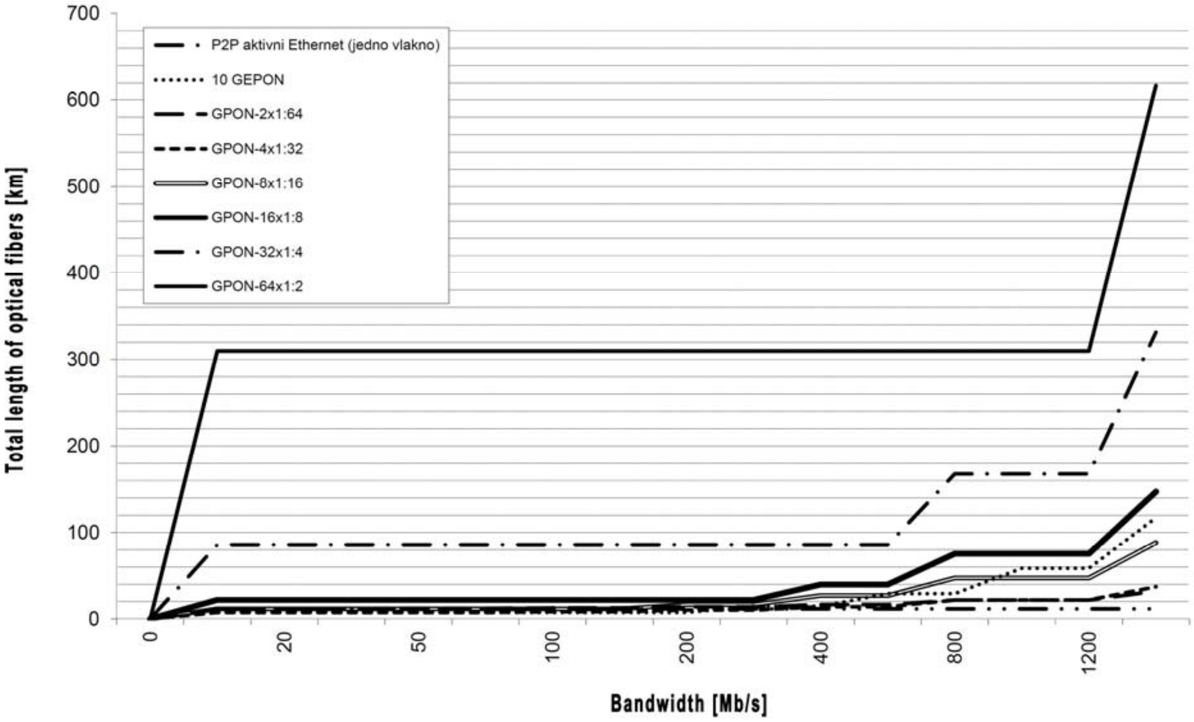
where *l* represents the distance between the CO and CDO, N_{max} is a maximum number of users per single OLT module, and N_{OLT} represents the number of OLT modules required to serve users on area of 1 km^2.

III. RESULTS AND DISCUSSION

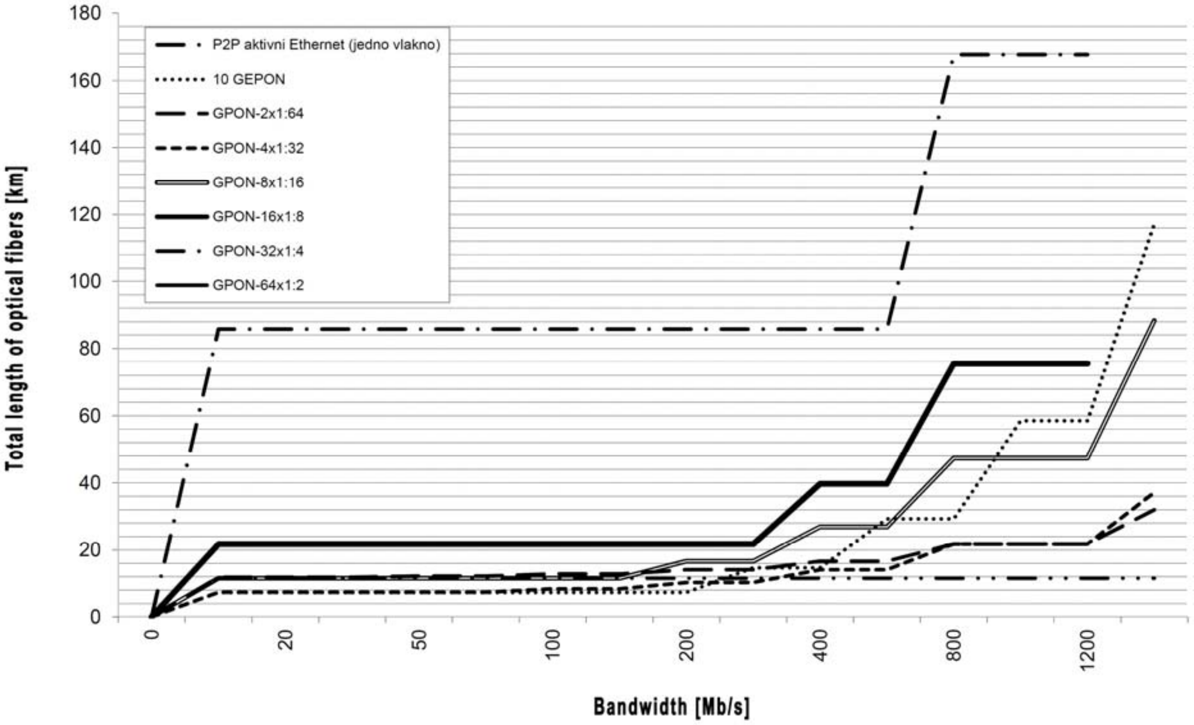
Comparative analysis of the dependence of the number and length of optical fibers by the increasing of users' density with guaranteed fixed bandwidth at the user side showed that the initial advantages or disadvantages of some technologies don't change. This result could be expected due to increased density of users only multiplies the number and length of optical fibers, in the same way in all technologies and corresponding topologies.

On the other hand, comparative analysis of the dependence of the number and length of optical fibers with an increase of guaranteed bandwidth on the user side and a fixed density of users shows that up to 50 Mb/s, GPON with initial topology 4x1:32 and 10GEPON, requiring a minimum length of optical fibers (Figure 4.a and 4.b). However, GPON technology in the base topology 4x1:32 has an advantage, because 10GEPON achieved these lengths without of contribution of optical fibers, in the segment of DO to the end user. GPON technology in the base topology 4x1:32 achieves the best balance between the required lengths of optical fibers for bandwidth up to 300 Mb/s.

We note that the figures 4.a) and 4.b) are identical but the Figure 4.b) shows a narrow range of optical fibers length for easy identification of typical graphics elements. Due to this reason, in Figure 4.b) we don't see GPON 64x1:2 topology. A typical transitions for all technologies and associated topologies are the same for all users density, and for this reason we show only the graphics in Figures 4.a) and 4.b).



a)



b)

For the bandwidth up to 40 Mb/s, second result, regarding the optimality, take the topologies of P2P active Ethernet and GPON topology 2x1:64 and 8x1:16. After increasing the bandwidth, required length of optical fibers for GPON topology of 2x1:64 increases. GPON topology 8x1:16 follows the topology of the P2P active Ethernet up to 150 Mb/s bandwidth, after which grows required length of optical fibers in this topology, and because of the rapid rise, quickly becomes weaker than GPON topology of 2x1:64. After this bandwidth, initial GPON topology 8x1:16 alternates with 10GEPON topology permanently.

For a bandwidth exceeding 400 Mb/s, topology of P2P active Ethernet becomes optimal, as might be expected, because the change of bandwidth doesn't affect on this topology only (in terms of passive part of the network), but it initially requires a greater length of optical fibers and thus the greater initial investment, especially in the version with two fibers per customer. It is also characterized by a great length of the optical fibers in part from the CO to the CDO as it degrades further in terms of benefits for implementation and optimal utilization of existing telecommunications infrastructure.

We considered the idealized topologies of selected technologies, in which all the splitters are equal. It will be a very rare case in reality than the case of topology with different types of splitters. Practical topologies have a combination of properties of idealized topologies, but due to the large number of possible combinations we didn't specifically discuss them. We can only say that these topologies can simultaneously have both good and bad qualities of the considered idealized topologies, and in concrete situation can be better or worse than them. We have to model each of these topologies with offered mathematical model and compared their characteristics with the characteristics of the idealized topologies, and on that basis make a conclusion about the optimality of their application in concrete situations.

Finally, let's say that this analysis considers only the passive part of the network, and after such a comparative analysis, that was conducted on the basis of mathematical modeling, it's necessary to consider other components (active equipment) and under the same conditions consider their techno-economic behavior at the change of guaranteed bandwidth to the user, and user density in the considered area. This will be the subject of our further research in this field.

IV. Conclusion

In terms of the required length of optical fibers, starting GPON topology 4x1:32, represents an optimal solution, when we talk about the passive part of the network, both for the initial investment and future needs, because in a large range of guaranteed bandwidth provides the best results. In terms of demand for PEHD pipes, micro pipes and the optical fibers number in some segments, this topology also shows the optimal results, both in terms of initial investment, but also in terms of the need for future investment in the passive part of the network, increasing the guaranteed bandwidth.

The study provided the best candidates for further research, which will include other crucial factors in choosing a final solution in concrete situation in practice.

In this study we confirmed the initial hypothesis, and also we fulfill both the set up tasks, and we opened a series of new questions and tasks for future research in this field.

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