Comparative Analysis of the Unavailability Factors for Two Types of Optical Cable Section Repair under Conditions of Gradual and Sudden Failures

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Abstract: The article presents a comparison of unavailability factors for two optical cable section types of repair under conditions of degradation and sudden failures. The first one involves replacing a section of optical cable in case of both degradation and sudden failure caused by outside interference. In the second type, the replacement of the optical cable section is carried out only in case of degradation failure. In case of a sudden failure, the optical cable is repaired by connecting at the point of breakage. To show the degradation process and analyze the impact of sudden failures, mathematical models of the semi-Markov process are used, which allow to determine the average recovery time and time to failure, the unavailability factor, as well as to estimate the duration of the degradation cycle. The degradation cycle covers the duration of optical cable operation from the initial state to the degradation failure, including the recovery time after sudden failures. This parameter can be an estimate the service life of optical cable or its section. At the same time, it is assumed that during operation, due to the cable sections replacement, the whole optical cable will be replaced. It is shown that the degradation cycle of the section in the first type grows with increasing the sudden failures rate, and in the second type, on the contrary, decreases compared to the planned value determined in the absence of sudden failures. The more frequent sudden failures occur, the more noticeable the difference in the values of the optical cable section unavailability factor calculated for both types of repairs. These results can be used to estimate the time needed to replace sections of optical cable due to degradation, as well as to select the optimal strategy for maintenance and repair of the access network optical cable.

1 INTRODUCTION

For many years, the issues of determining the optical cable service life have been discussed in publications [1-12, etc.]. This problem has gained particular interest in recent years, since the service life of the laid optical cable has already exceeded the warranty period specified by the manufacturer. It should be noted that the service life of an optical cable is usually understood as the time that determines the need to replace the laid optical cable due to the fact that its limiting state caused by degradation processes has occurred. The limiting state is understood as the object state in which further operation is unacceptable or impractical, or restoration of its functional state is impossible or impractical [13].

Degradation processes in an optical cable can lead to its rupture, which is determined by its mechanical reliability [7], or to an increase in the signal attenuation coefficient, at which the level at the receiver input may become below the sensitivity threshold (optical reliability).

From a mechanical point of view, the durability of any object, including optical fiber, is estimated:

- the initial strength of the optical fiber;
- the presence and depth of microcracks on the fiber surface;
- the rate of optical fiber degradation, determined by the rate of microcracks growth on its surface;

- an environment that leads to a weakening of the material from which the optical fiber is made.

There are three stages of microcracks development. The first stage is the stage of microcrack nucleation; the second is the stage of microcrack depth growth, the third lasts for seconds and ends with the rupture of the optical fiber. The second stage lasts for years, and it is mainly this stage that determines the service life of the optical cable.

In [1], various scenarios for predicting the service life of optical fiber in a cable communication line are considered. The forecast is based on an expression borrowed from [14, 15]:

$$t_a = t_p \cdot \left(\frac{\sigma_p}{\sigma_a} \right)^{n_q} \cdot \left\{ \left[1 - \frac{\ln(1-F)}{N_p \cdot L_{of}} \right]^{\frac{1}{m_S}} - 1 \right\}, \qquad (1)$$

where t_p is time to fiber failure obtained during fiber testing; σ_p is the load at which testing was carried out; L_{of} is the length of the fiber for which the service life is predicted; N_p is the number of fiber breaks during testing under load; n_q is the strength parameter of quartz glass; m_s is the Weibull distribution parameter; F is the probability fiber failure; σ_a is the load applied to the fiber during its service life.

So, in order to determine the time a fiber section damage (breakage, failure), it is necessary, according to (1), to have the results of cable testing, to know the load on the fiber and the Weibull distribution parameter m_s. In this case, the time of the fiber failure depends on the probability of failure F, which must be set. In fact, using (1), it is only possible to determine the probability of optical fiber failure during t_a, and not its lifetime, i.e. the time from the start of operation to the fiber replacement. According to [16], the value ($1-F$) is chosen to be 0.95. It is noted in [1] that the load on individual sections of the fiber-optic line may differ; therefore, it is proposed to calculate the so-called equivalent load, on the basis of which the service life of the fiber as a whole is predicted.

The widespread approach presented above to determining the replacement time of an optical cable caused by fiber degradation seems formal, since one-time costs of replacing an optical cable and information losses caused by the time spent on replacing an optical cable are not taken into account. In addition, it should be borne in mind that the load on the cable varies in different sections. Similar questions arise when considering the replacement period of an optical cable with an approach based on optical reliability.

In this regard, it is proposed to consider an optical cable with a length of L km as a set of n sequentially connected sections with a length of l km, where $n = L/l$, and to consider, in case of a degradation failure [13], the replacement of sections as they fail according to the rules determined by the method of maintenance and repair of these sections, taking into account the occurrence of sudden failures. During the maintenance process, cable sections can be repaired by connecting at breakage points, replacing individual cable sections, and replacing the entire optical cable. Deciding which repair will be the most profitable is a difficult technical and economic task [17]. Thus, replacing the entire optical cable is very expensive and is performed when the cost of replacing the entire cable will be less than the cost of replacing individual sections and making connections.

We will consider the service life of the sections, assuming that it is determined by degradation processes that lead to a break in the optical cable section or exceeding the signal attenuation of a critical level. So, degradation processes determine the service life of optical cable sections and the need to replace them. After a certain time all sections of the optical cable will be replaced with new ones. It is clear that it will take significantly less time to replace the section at $l \ll L$ than to replace the entire cable, and the costs associated with such a replacement will be stretched over time and incomparable with the costs of replacing the cable as a whole.

The article compares unavailability factors for two types of optical cable repair under conditions of gradual (degradation) and sudden failures, which differ by the influence of sudden failures on the degradation process. The first type of repair involves replacing a section of optical cable both in case of degradation failure and sudden failure [3, 4]. We assume that during operation, due to the replacement of cable sections, the whole optical cable will be replaced. Thus, only the replacement of cable sections is considered. Then the degradation cycle of the entire optical cable, characterizing its lifetime, will tend to infinity. The degradation process in [3, 4] is described by the Markov process of pure death. Sudden failures at the same time lengthen the degradation cycle, since after a sudden failure, the section is replaced with a new one. The second type involves replacing the section only in case of degradation failure. At sudden failure, which is accompanied by a rupture of the optical cable in the section, communication is restored by welding or mechanical connection at the point of breakage.

It should be noted that both types of repair can be considered in relation to mechanical and optical reliability.

To determine the unavailability factor for the first and second types of repair, we divide the planned degradation cycle, determined in the absence of sudden failures, into n intervals of T_D duration. Each interval represents the corresponding degradation state of an optical cable section. In the last n^{th} state, a degradation failure occurs, leading to the replacement of an optical cable section. In each such condition, a degradation process takes place and a sudden failure may occur, which has an obvious character. Sudden failures are distributed exponentially with the same rate in each state. After each sudden failure, the section is restored, while during the restoration the cable is not used for its intended purpose, that is, it is inoperable. The impact of sudden failures is considered under conditions of continuous reliable monitoring.

The unavailability factor is determined by the expression [3]:

$$F_U = \frac{T_{DS}}{T_{CD}}, \tag{2}$$

where T_{DS} is average down state time per degradation cycle; T_{CD} is average duration of the degradation cycle.

When creating mathematical models for the conditions described above, semi-Markov process state transitions diagrams are compiled, simulating the degradation process.

2 STATE-TRANSITIONS DIAGRAM OF THE OPTICAL CABLE SECTION FOR THE FIRST TYPE OF REPAIR

The type of repair involves replacing a section of optical cable because of a sudden failure. The elimination of sudden failure is carried out with recovery rate μ_1. After restoration, the transition to the initial state of degradation is carried out, as shown on Figure 1, which shows the state-transitions diagram on the degradation cycle.

There are following signs on the Figure 1: D_i – i^{th} degradation state, $i = 1, 2, ..., n$; R – recovery after sudden failure; μ_1 – recovery rate of a section after sudden failure; μ_2 – recovery rate of a section after degradation failure; p_D - probability of transition between two degradation states (probability of that a sudden failure will not occur in this state of degradation); q_D - the probability of transition to recovery after a sudden failure in one state of degradation (the probability of a sudden failure in a state of degradation) [3, 4].

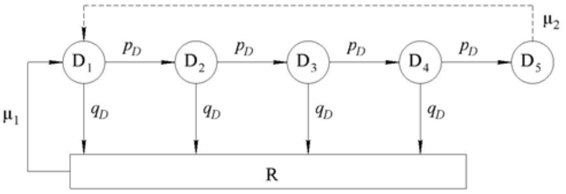


Figure 1: The state-transitions diagram on the degradation cycle for the first type of repair at $n = 5$.

In each degradation state a sudden failure may occurs. This event in the time interval T_D is characterized by two probabilities [18]:

$$p_D = \exp(-\lambda \cdot T_D);\ q_D = 1 - \exp(-\lambda \cdot T_D), \tag{3}$$

where λ is a sudden failure rate.

The average time of down state during the degradation cycle is determined by the expression [3]:

$$T_{DS1} = n \cdot q_D \cdot \theta_{DS} + T_R = \\ = n \cdot q_D \cdot \frac{\lambda \cdot T_D - q_D}{\lambda} + \left(\frac{1 - p_D^{n-1}}{p_D^{n-1}} \cdot \frac{1}{\mu_1} + \frac{1}{\mu_2} \right), \tag{4}$$

where θ_{DS} is the average time spent in the down state after a sudden failure in a state of degradation, determined by (5) in [3]; T_R is the average recovery time on the degradation cycle, determined by (14) in [3]; μ_1 is the cable section recovery rate after a sudden failure; μ_2 is the cable section recovery rate after degradation failure; p_D and q_D are defined by (3).

The average duration of the degradation cycle is determined by the expression [3]:

$$T_{CD1} = \frac{1 - p_D^{n-1}}{(1 - p_D) \cdot p_D^{n-1}} \cdot T_D + T_R. \tag{5}$$

3 STATE-TRANSITIONS DIAGRAM OF THE OPTICAL CABLE SECTION FOR THE SECOND TYPE OF REPAIR

The second type of repair is characterized by the restoration of an optical cable section after a sudden failure by connecting at the breakage point.

Let's consider the i^{th} degradation state. At a sudden failure the current degradation state consists of three parts: before the failure D'_i, recovery R_i and after the sudden failure D''_i (Figure 2).

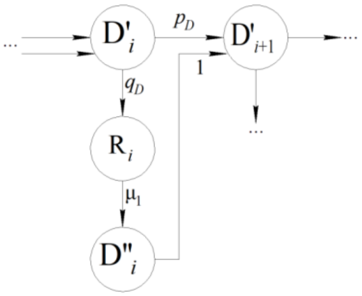


Figure 2: The state-transitions diagram on one degradation state for the second type of optical cable repair.

There are following signs on the diagram Figure 2: i − degradation state number, i = 1, 2, ..., n-1.

The degradation state is estimated by the signal attenuation parameter, which value increases from state to state. In some state, in the absence of sudden failures, the attenuation parameter reaches a limit value at which a degradation failure appears. After the occurrence of such a failure, the cable section is restored by replacing it with a new one.

The initial state of the degradation cycle is the state corresponding to the minimum value of the attenuation parameter. In the current state of degradation, the attenuation parameter increases by the value Δb in the absence of sudden failures. Raising the attenuation parameter in one state is transferred to the next degradation state when switching to it. Sudden failures can cause different changes in the attenuation parameter. This phenomenon is taken into account using the coefficient η. At η = 0 sudden failures do not affect the degradation process; at η = 1 sudden failures have the same effect as the degradation process in one state; at η > 1 sudden failures have a greater impact compared to the degradation process in one state.

The process of transitions between states in the degradation cycle is shown on Figure 3.

The transition $D_i \rightarrow D_{i+1}$ occurs at the end of T_D regardless of a sudden failure presence or absence. At the same time, from the point of view of reliability, the interval T_D consists of two parts: up (D'_i and D''_i) and down (R_i) parts.

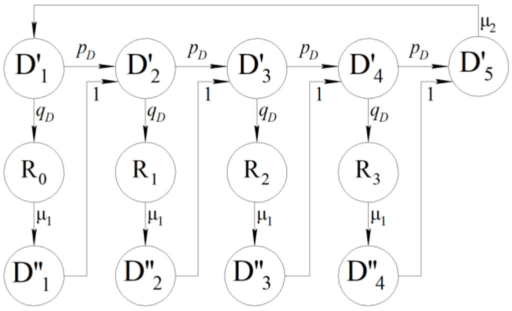


Figure 3: The state-transitions diagram on the degradation cycle for the second type of optical cable repair at n = 5.

In any case, in the state D_{i+1}, the attenuation parameter increases by the value Δb due to the degradation process in the state D_i. However, an increase in the attenuation parameter due to a sudden failure happens only if a sudden failure occurs. Since the probability of a sudden failure is q_D, this increase will be on average by the amount of $\eta \cdot \Delta b \cdot q$.

The increase in the attenuation parameter is expressed as follows:

$$b_{i+1} = b_i + \Delta b + \eta \cdot \Delta b \cdot q_D \,, \tag{6}$$

where b_i is the parameter of signal attenuation in the i^{th} degradation state.

Taking into account (6), the calculation of the attenuation parameter in the state D_i under the condition $b_0 = 0$ is:

$$b_i = i \cdot (1 + \eta \cdot q_D) \cdot \Delta b, \ i = 1, 2, \ldots, n \,. \tag{7}$$

In accordance with (7), at $\eta \neq 0$ and $q_D \neq 0$, the increase in the signal attenuation parameter during the transition from state to state will be greater than the planned value Δb. Degradation failure in the absence of sudden failures will occur at the value of the attenuation parameter $n \cdot \Delta b$. Degradation failure, taking into account sudden failures, will occur when the condition $b_i \geq n \cdot \Delta b$ is fulfilled, which is expressed by the inequality:

$$I \geq \frac{n}{1 + \eta \cdot q_D} \,, \tag{8}$$

where I is the number of the condition with degradation failures. This number is simultaneously the number of states included in the degradation cycle. It is obvious that $I < n$.

When condition (8) is fulfilled, the degradation cycle ends in the state D_I the optical cable section is replaced, then there is its further operation with a new degradation cycle.

In each state of degradation, during the restoration of the section, the optical cable is not used for its intended purpose, i.e. it is on down state. The average recovery time on one state is q_D/μ_1, where q_D is determined by (3).

The down state average time of an optical cable during the degradation cycle, taking into account the time to replace the entire cable after a degradation failure, is determined by the expression:

$$T_{DS2} = \frac{\mu_1 + I \cdot \mu_2 \cdot q_D}{\mu_1 \cdot \mu_2}. \quad (9)$$

The average degradation cycle time is:

$$T_{CD2} = I \cdot T_D + 1/\mu_2 . \quad (10)$$

4 COMPARATIVE ANALYSIS OF THE OPTICAL CABLE SECTION UNAVAILABILITY FACTORS FOR VARIOUS TYPES OF REPAIR

The unavailability factor of an optical cable section per degradation cycle for the first type of repair, taking into account (2), is determined by the expression:

$$F_{U1} = \frac{T_{DS1}}{T_{CD1}}, \quad (11)$$

where T_{DS1} is determined by (4); T_{CD1} is determined by (5).

The unavailability factor of an optical cable section per degradation cycle for the second type of repair, taking into account (2), (8)-(10) is determined by the expression:

$$F_{U2} = \frac{T_{DS2}}{T_{CD2}} = \frac{\mu_1 + \frac{n}{1+\eta \cdot q_D} \cdot \mu_2 \cdot q_D}{\left(1 + \frac{n}{1+\eta \cdot q_D} \cdot \mu_2 \cdot T_D\right) \cdot \mu_1}. \quad (12)$$

Let's consider the behavior of the unavailability factors defined by (11) and (12) for both types of repair at different values of the sudden failures rate λ. To do this, let enter the following initial data:

- the planned number of degradation states n=30;
- duration of one degradation state T_D = 1 year = 8760 h;
- the recovery rate after a sudden failure for the first type of repair μ_1 = 1/10 1/h, for the second type of repair - 1/4 1/h;
- the recovery rate after degradation failure μ_2 = 1/10 1/h [19].

In the absence of sudden failures over the entire interval of the planned degradation cycle, an increase in the attenuation parameter due to degradation in one state can be assumed to be equal Δb = 0.2 dB with an energy reserve of 6 dB [18, 20], when a planned degradation failure occurs.

In the presence of sudden failures, restoration of the optical cable after failure increases the attenuation parameter by 0.05 dB for the welded method of connecting optical fibers and by 0.5 dB for the mechanical connection of optical fibers [5, 18]. Thus, the increase in the attenuation parameter due to a sudden failure $\eta \cdot \Delta b$ is equal 0.05 dB or 0.5 dB at Δb = 0.2 dB. Then the sudden failure impact factor η is 0.25 and 2.5, respectively. For calculations, let's take the worst case when η = 2.5.

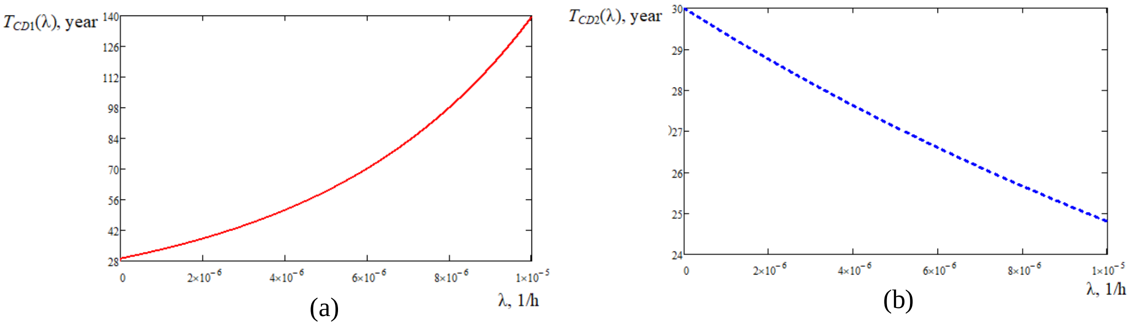
Figure 4 (a), (b) shows the dependence of the average degradation cycle time of an optical cable section (in years) on the sudden failures rate $\lambda = 0, 10^{-9}, \ldots, 10^{-5}$ 1/ч.

According to Figure 4, it can be seen that at the first type of repair, the growth in the number of sudden failures increases the degradation cycle of the cable section, which is associated with more frequent replacement of the entire section with a new one. The second type of repair is characterized by a decrease in the duration of the degradation cycle compared to the planned value, which is associated with the appearance of additional attenuation due to the restoration of the connection at the breakage point.

Figure 5 (a), (b) shows the dependence of the optical cable section unavailability factor F_U at the degradation cycle on the sudden failures rate $\lambda = 0, 10^{-9}, \ldots, 10^{-3}$ 1/ч.

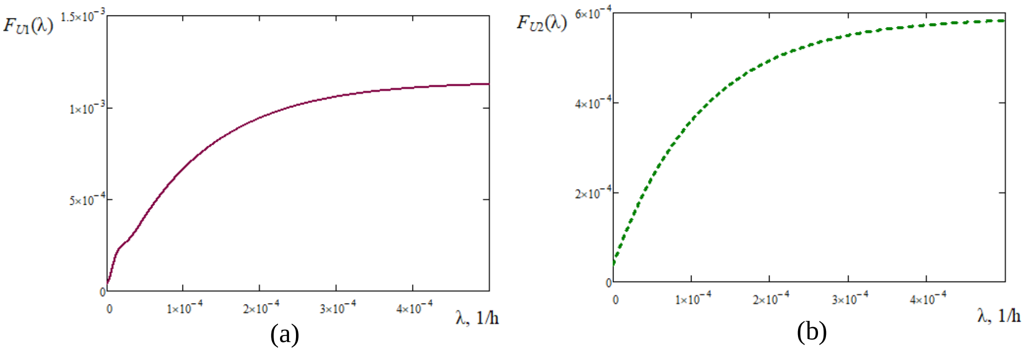
The values of the unavailability factors F_{U1} и F_{U2} at different values of λ are shown in Table 1.

At the second type of repair the values of the unavailability factor are lower than at the first type, as follows from Table 1. Moreover, the more often sudden failures occur, the more noticeable the difference. This is due to the repair time, since it takes longer to replace the entire section of the optical cable than to weld or mechanically connect the fiber breakage point.



(a) (b)

Figure 4: Dependence $T_{CD}(\lambda)$ for the first (a) and second (b) types of optical cable repair.



(a) (b)

Figure 5: Dependence $F_U(\lambda)$ for the first (a) and second (b) types of optical cable repair.

Table 1: The values of the unavailability factor for two types of optical cable repair.

Parameter	Value						
λ, 1/h	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}
F_{U1}	$3.937\cdot10^{-5}$	$3.941\cdot10^{-5}$	$3.985\cdot10^{-5}$	$4.47\cdot10^{-5}$	$1.684\cdot10^{-4}$	$6.657\cdot10^{-4}$	$1.14\cdot10^{-3}$
F_{U2}	$3.806\cdot10^{-5}$	$3.81\cdot10^{-5}$	$3.853\cdot10^{-5}$	$4.286\cdot10^{-5}$	$8.432\cdot10^{-5}$	$3.6\cdot10^{-4}$	$5.896\cdot10^{-4}$

5 CONCLUSIONS

The models presented in the article can be used to evaluate the degradation cycle of an optical cable, which determines the period of its replacement due to cable optical fiber aging. Two types of an optical cable repair due to a sudden failure are considered.

In the first type of repair, the optical cable section is replaced in case of a sudden and degrading failure, as a result of which, after some time, the entire cable will be replaced.

In the second type of repair, the cable section is restored due to a sudden failure, the connection is made at the breakage point, which leads to an increase in signal attenuation on the optical cable section, and its degradation cycle decreases compared to the planned value of 25-30 years. Thus, it becomes possible to specify the time of replacement of an optical cable section due to degradation.

It is shown that the presence of sudden failures in the first type of optical cable repair leads to an increase in the degradation cycle, and in the second type of repair – to a decrease in the degradation cycle of the optical cable.

It is advisable to use the second type of repair for restoration at the early stages of optical cable operation, and at the end of the planned degradation cycle – the first type, which will increase the time before replacing the whole cable.

Issues related to the efficiency of using a particular type of repair require consideration not only from the point of view of reliability, but also the economic costs of cable restoration due to failure. At the same time, it is obvious that the cost of replacing an optical cable section exceeds the cost of connecting the cable at the breakage point.

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