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Maintaining the reliability of communication networks while continuing operation of optical cables beyond their warranty period

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Abstract. Currently, an increasing number of fiber-optic communication lines are reaching the end of their predetermined service life, yet the quality indicators of these lines still allow for continued operation. To extend the actual operational life of these lines, it is necessary to conduct high-quality monitoring of both the current status of all components and the dynamics of key indicators. This article proposes a method for addressing the challenge of maintaining communication network reliability while continuing to use optical cables after their warranty period has expired. A study of random values of the attenuation coefficient and polarization mode dispersion of an optical fiber, supported by actual operational data from a network segment, shows high temporal stability in the attenuation coefficient and polarization mode dispersion of optical fiber type G.652. This conclusion allows us to discuss the continued operation of optical cables after the warranty period. To analyze the key aging metric, mathematical models are used that take into account the physical and chemical properties of cables as well as the conditions of their proof-tests. Using an example related to the current state of Russian fiber optic networks, we calculate the number of emergency reserve elements necessary to maintain the reliability of their operation. Practical recommendations for the placement of emergency reserve are also provided.

Key words and phrases: communication networks, fiber-optic cables, service life, operational reliability index

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1. Introduction

By definition, the service life of a cable is the period of time from the start of its operation until it reaches its limit state, where further operation becomes unacceptable, impractical or impossible, or restoration of its operational state is not feasible. This limit state is determined in advance in regulatory, technical, or project documentation. Thus, on the one hand, it may seem contradictory to talk about the reliability of a communication transport network when its basis—the optical cable [1]—has reached its limit state.

However, it is difficult to determine the exact limit state of an optical cable. In practice, the term "service life" refers to the duration of time determined by the manufacturer, during which the failure rate caused by aging (fatigue) is not expected to increase exponentially. This usually occurs between 25 and 30 years. So, the service life can be seen as an extrapolated indicator of reliability, which can be estimated (in point or on interval) by extrapolating calculations, tests, and/or operational data to a different duration of operation and different operating conditions.

It is important to consider two factors. Firstly, the expected service life of optical cable in general and optical fibers in particular is determined with a high degree of uncertainty, and therefore, cable manufacturers specify this in the passport-certificate for the construction length with a considerable margin. Secondly, operating companies have technical and organizational resources to influence the operational reliability indicator, which can be assessed by point or interval analysis based on operational data. In particular, the conditions of laying and operation with a limitation of the permissible bending radii of optical fibers can significantly reduce the mechanical loads on them and increase their service life [2].

Based on the above, it is clear that the problem formulation is correct and relevant. To find an informed solution, we will separately consider the issues of the temporal stability of optical fiber parameters.

2. Study of the temporal stability of the optical fiber attenuation coefficient

The main distinguishing feature of optical fiber as a signal transmission medium is the random nature of the attenuation coefficient. This coefficient depends on a number of design parameters, including the longitudinal uniformity of the core, the eccentricity and non-roundness of the core, and the longitudinal uniformity of the material. Other factors that can affect the attenuation include extraneous inclusions in the quartz, microcracks, and microbends.

The culture of producing optical fiber and optical cable significantly impacts the attenuation coefficient value. Studies [3–5] indicate that the range of the attenuation coefficient spans from the minimum values determined by the so-called Rayleigh (or dipole) scattering [3] to the maximum values defined in manufacturer technical specifications.

The same can be said about spliced optical fiber connections. Almost everywhere, they are made by welding. In this case, optical power losses depend on several factors, including the fiber chopping angle, the tolerances on the outer diameter of the optical fiber, the eccentricity and non-roundness of the core, the welding mode, and the compressive force. These factors all have an inherent random nature, which means that the optical loss value is also random. The minimum value of the loss is zero, while the maximum value is determined by the technical specifications for connector couplings.

The resulting attenuation of optical fiber in the amplifying (regeneration) span is thus a sum of random variables. In general, finding the distribution law for the sum of random variables is a difficult task. However, in this case, where there are a large number of terms due to the long length of the span, there is a simple and fairly accurate solution to the problem. Based on the central limit theorem [6], it can be argued that the distribution of the total attenuation in the amplification span will follow the normal distribution. The numerical values of the mean and standard deviation of this distribution, $\overline{a}_L$ and $\sigma(a_L)$, respectively, can be defined as follows

$$\overline{a}_L = \overline{\alpha}L + \overline{a}_{sc}\left(\frac{L}{l_{cs}} - 1\right),$$

$$\sigma(a_L) = \sqrt{\sigma^2(\alpha)L + \sigma^2(a_{sc})\left(\frac{L}{l_{cs}} - 1\right)},$$

where $\overline{\alpha}$ is the average of the attenuation coefficient; $\overline{a}_{sc}$, $\sigma(a_{sc})$ are the average and the standard deviation of losses at the optical fiber spliced connection; L is the length of the regeneration span, l_{cs} is the length of optical cable construction span.

The right bound of the confidence interval with probability 0.996 is usually used as a norm in practice. This means that, on average, one fiber out of every 1000 would have an attenuation slightly greater than that calculated by the formula

$$a_L(0.9986) = \overline{\alpha}L + \overline{a}_{sc}n + 3\sqrt{\sigma^2(\alpha)L + \sigma^2(a_{sc})n},$$

where $n = \frac{L}{l_{cs}} - 1$.

Let us consider the initial laws of distribution of the attenuation coefficient and losses in spliced optical fiber connections. A number of studies and ITU-T recommendations [7–9] indicate that the attenuation coefficient follow a normal probability distribution. The range of its value, denoted by $\Delta\alpha$, extends from the lowest value of Rayleigh losses, ($\alpha \approx 0.8/\lambda^4$), to the highest value specified by the manufacturer or in ITU-T recommendations [7–9]. The mathematical expectation of this distribution corresponds to the midpoint of the range, $\Delta\alpha/2$, while the standard deviation is one-sixth of the range, $\Delta\alpha/6$.

The results of the study [10] indicate, that the attenuation coefficient of optical fiber

- is random;
- with high accuracy obeys the normal Laplace–Gauss law with a mathematical expectation of 0.193 dB/km when the wavelength is 1.55 μm;
- in typical specifications (0.35 and 0.22 dB/km) takes values close to the maximum;
- in the range from 0.14 dB/km (Rayleigh scattering) to 0.22 dB/km has a standard deviation equal to 0.013 dB/km if determined by the three-sigma rule.

To assess temporary changes, we determine the confidence interval of the mathematical expectation Δ with a confidence probability of 0.95 (t = 1.96 is a parameter from Laplace tables).

$$\Delta = \sigma \times t/\sqrt{m} = 1.96 \times 0.013/\sqrt{8} = 0.009,$$

where m is the number of optical fibers measured. Thus, the confidence interval for the mathematical expectation of the attenuation coefficient lies between the values of 0.184 and 0.202 dB/km.

After many years of research on optical fibers under real operating conditions, we have obtained the following results. To illustrate, let's consider the optical losses measured on eight optical fibers of a separate amplifying section within the Kadala–Skovorodino regeneration span in Siberia. Table 1 shows the calculation of average attenuation coefficient based on optical loss measurements.

As can be seen from Table 1, all average sample values of the attenuation coefficient (0.190–0.197) are within the confidence interval of the mathematical expectation (0.184–0.202). These results coincide with a number of studies conducted on the parameters of optical fibers over several years [11]. This indicates that the attenuation coefficient of G.652 optical fiber is highly stable over time.

3. Study of the temporal stability of optical fiber chromatic and polarization-mode dispersion

The chromatic dispersion of an optical fiber over a given distance is calculated by multiplying the chromatic dispersion coefficient by the length of that distance [12]. Thus, chromatic dispersion accumulates in proportion to the length of an optical fiber.

Table 1

Optical loss statistics

Optical fiber #	Average losses in weldings, dB	Welding losses, normalized to a length of 1 km, dB/km	Optical losses normalized to a length of 1 km, dB/km	Attenuation coefficient, dB/km
05	0.022	0.004	0.200	0.196
06	0.044	0.009	0.201	0.192
09	0.063	0.013	0.203	0.190
10	0.027	0.005	0.200	0.195
13	0.043	0.009	0.204	0.195
14	0.021	0.004	0.201	0.197
15	0.035	0.007	0.202	0.195
16	0.019	0.004	0.198	0.194

The term "single-mode fiber" is relative, as there can be no truly single-mode fiber. Strictly, a "mode" is a solution to Maxwell's equation for a dielectric waveguide. These equation for a cylindrical waveguide with a core-to-cladding diameter ratio (μm) of 8-10/125 always have two solutions, producing two modes with the same attenuation coefficient but with two polarization planes shifted by 90 degrees from each other. Due to various factors such as structural inhomogeneities in the optical fiber and local mechanical stresses, polarization mode dispersion (PMD) has a pronounced random character and accumulates in proportion to the square root of the amplifying (or regeneration) span length. The maximum value of PMD is typically characterized by its 99.99th percentile.

For G.652 optical fiber, the chromatic dispersion coefficient at the 1.55 μm wavelength is 18 ps/(nm$\times$km), the minimum and maximum values of the coefficient in the 3rd optical transparent window (1525–1625 nm) are 14.5 and 20.5 ps/(nm$\times$km) respectively, and the maximum value of PMD, normalized to a length of 1 km, is equal to 0.5 ps/km$^{1/2}$. Chromatic dispersion coefficients and PMD values, normalized to 1 km, measured on 8 optical fibers of a separate amplifying span inside the Kadala–Skovorodino regeneration span in Siberia, are given in Table 2.

The data in Table 2 shows: a) the dispersion parameters of the optical fiber are stable over time; b) the average of the maximum PMD values normalized to a length of 1 km (0.235 ps/km$^{1/2}$) is significantly less than the normalized quantile (0.5 ps/km$^{1/2}$). With this value of the normalized PMD, the total value of PMD on the entire regeneration span Kadala–Skovorodino (1027.3 km) will be no more than 7.5 ps.

Thus, the research findings indicate a high degree of temporal stability in the attenuation coefficient and PMD of G.652 optical fiber. These results allow us to proceed with solving the main problem.

4. Russian transport networks features

Within the context of this task, it is important to note the following features of the transport networks that form the Russian information infrastructure.

Table 2

Chromatic and polarization-mode dispersion

Characteristic	**Optical fiber #**							
	05	06	09	10	13	14	15	16
Chromatic dispersion coefficient, minimum, ps/(nm×km)	14.94	14.93	14.86	14.88	14.88	15.03	14.83	14.91
Chromatic dispersion coefficient, maximum, ps/(nm×km)	20.19	20.18	20.10	20.16	20.14	20.21	20.19	20.18
Maximum PMD value, normalized to a 1 km, ps/km$^{1/2}$	0.216	0.238	0.256	0.283	0.227	0.205	0.224	0.231

1. The main backbone fiber-optic communication lines (FOCL) of national transport networks were built in a relatively short period of time in the late 1990s and early 2000s, and they are currently approaching the service life limits of 25–30 years [13, 14]. At the same time, the cable infrastructure is not only an expensive component of the fiber optic network, but also an element requiring special operational support [15].
2. In accordance with the requirements for the construction of FOCL, the nominal length of elementary cable sections (ECS) has been calculated based on the maximum values of the attenuation coefficient and losses in permanent connection of optical fibers [16]. The maximum length has also been calculated taking into account three-sigma deviations, which corresponds to a 99.86% probability of attenuation point. Statistical normalization allows for an increase in the length of individual ECS of 20–35% relative to the specified value. However, this reduces the reserve in optical transmission system power budget, which is so necessary when the failure rate of the optical fiber increases after the end of the cable's service life.
3. The design and technical features of optical cables have led to the development of a fundamentally new technology for constructing long-distance communication networks—transport multichannel communication (TMC). In all-dielectric optical cables, it has been possible to "peel off" the massive outer coatings from the lightweight optical core, turning the outer covers into an independent protective polyethylene pipe (PPP), which is an element of the cable sewer, and the optical core into a small-sized optical cable that is blown inside the PPP.

When constructing the engineering infrastructure of transport networks using TMC technology, first a PPP package is laid along the route, then viewing devices are installed and, finally, optical cables are blown into the formed channels. TMC technology can be implemented along highways, and/or along the routes of decommissioned copper communication cables.

The high competitiveness of TMC's technology is based on a range of features, including legal, financial, technical, and organizational aspects. These features include universal right of passage, an extended construction season, lower final capital and operating costs, long service life (TMC lasts 50 years, optical fiber 25–30), localization of accidents using a geographic information system, low damage density (less than 0.1 per 100 km of TMC per year), short cable recovery times (within 8 hours), comfortable ambient temperature from optical fiber aging point of view (−2°C – +18°C) and high protection against vandalism, and ammunition explosions.

5. Aging of optical fiber

In accordance with the classification adopted in the reliability theory, optical fiber is an object of a specific purpose, continuous long-term use, renewable during its service life and susceptible to aging. The strength theory reveals the process of aging (fatigue) of solids through the thermal fluctuation mechanism of silicate-oxygen bonds. Brownian motion of atoms constantly breaks and recreates these bonds. At the moment when the number of broken bonds significantly exceeds the number of restored ones, a microcrack forms. The presence of even a small tensile force provokes crack growth.

The basic reliability model of a fiber that has passed proof tests is presented as follows

$$t_f = \left\{ \left[B^{\frac{m}{n-2}} S_0^m \frac{L_0}{L} \ln \frac{1}{1-F} + \left(\sigma_p^n t_p\right)^{\frac{m}{n-2}} (1+C)^{\frac{m}{n-2}} \right]^{\frac{n-2}{m}} - \sigma_p^n t_p \right\} - \frac{B}{\sigma_a^2},$$

where $C = \dfrac{\frac{B}{\sigma_p^2} - \frac{t_u}{n+1}}{t_p}$, when the loading time of the proof test is less than or equal to the unloading rate $t_u \le (n-2)\frac{B}{\sigma_p^2}$; B and n—fiber fatigue parameters; m—Weibull modulus of the unimodal Weibull distribution; S_0^m—Weibull strength measure; F—tensile force; σ_p—load during proof test; $t_p = t_d + \frac{t_l + t_u}{n+1}$; t_d—holding time; t_l and t_u are the loading and unloading times of the proof test, respectively; L_0/L is the ratio of the test length L_0 to the simulated operational length L.

The intrinsic inert strength of quartz in liquid nitrogen is about 14 GPa [17, 18]. The typical fiber load during the proof test is 0.7 GPa, and the recommended permanent operating load is no more than 80% of the load during factory technical control. In this case, with a probability close to 1, the service life of optical fiber is 25 years. After that period, the rate of damage to the optical fiber will increase.

6. Aging of optical cable

The basis of the design of optical cables is plastics that are susceptible to aging. The aging process occurs when plastics gradually lose substances over time, such as plasticizers (polyvinylchloride) and antioxidants (polyethylene et al.), which are slowly evaporated.

Evaporation (diffusion) of plasticizers plasticizer is described by Fick's law

$$\frac{d}{dx}\left(D\frac{\partial c}{\partial x}\right) = \frac{dc}{d\tau},$$

where c is the plasticizer concentration per unit volume, kg/m^3; x—diffusion depth, m; τ—time, s; D—diffusion coefficient, m^2/s.

Chemical and physical parameters of plasticizers are given in Table 3.

The partial vapor pressure of the plasticizer P is expressed by the approximate ratio

$$P \approx P_0 e^{-\frac{E}{RT}},$$

Table 3

Chemical and physical parameters of plasticizers

Parameter name	**Parameter value for plasticizer**		
	Dibutyl phthalate	Dioctyl phthalate	Tricresyl phthalate
Chemical formula	C11H22O4	C24H38O4	C21H21O4P
Molecular mass μ, g/mol	278	390	368
Density, g/cm^3	1.046	0.986	1.162
Partial pressure constant P_0, Pa	2.1×10^{11}	8.2×10^{11}	9.4×10^{12}
Evaporation energy E, J/mol	7.40×10^4	8.73×10^4	10.44×10^4

where P_0—partial pressure constant given in Table 3; $R = 8.314$ J/(mol×K)—universal gas constant; T—temperature, K.

The plasticizer evaporation rate constant, reduced to the effective operating temperature k_{re}, is expressed by the following equation:

$$k_{re} = k_i e^{-\frac{E}{R}\left(\frac{1}{T_p} - \frac{1}{T_i}\right)},$$

where k_i is the evaporation (desorption) rate constant of the plasticizer at the i-th temperature, s^{-1}; T_i—test temperature, K; T_p—effective operating temperature of the product, K. The dependence of the rate of antioxidant consumption on temperature is determined by the Arrhenius equation

$$k_2 = k_b e^{a\vartheta}, \tag{1}$$

where k_2 is the constant of the rate of antioxidant consumption during polyethylene oxidation; $k_b = k_{02} e^{-\frac{U_A}{RT_b^2}}$; $a = \frac{U_A}{RT_b^2}$; $\vartheta = T - T_b$; U_A—activation energy of the antioxidant consumption process; k_{02}—constant factor; T_b is the base temperature above which the oxidation reaction proceeds at a rate recorded by a microcalorimeter.

According to (1), the deviation in antioxidant concentration has the form

$$W_a^0 - W_a = \frac{k_b}{a\vartheta_T}(e^{a\vartheta} - 1),$$

where W_a^0 is the initial concentration of the antioxidant; W_a—the final concentration of antioxidant; ϑ_T—rate of temperature change.

As a result of aging, the mass of plastic changes (decreases) over time. So, a diagnostic parameter for cable durability is

$$\Delta G = 100\frac{G_i - G_f}{G_i}\%,$$

where ΔG—relative mass loss, %; G_i—initial sample weight, mg; G_f—final sample weight after heating, mg.

Along with the change in mass due to evaporation of the plasticizer or antioxidant the electrical conductivity, dielectric loss tangent, electrical strength, elongation at break, deformation and deformation rate of plastics, glass transition temperature and cold resistance of plastics change. These physical characteristics can also be used to determine the durability ratings.

7. Emergency cable reserve

When the risk of failures of a fiber-optic cable increases, it is advisable to optimize the emergency reserve (ER), which includes the estimated cable length, couplings, and fittings.

For optimization, the initial data for calculation are determined:

- the number of identical elements with the same time-to-failure value in a component of the i-th type (cable, coupling)—m_i;
- failure rate of elements of the i-th type—λ_i, 1/hour;
- time periods $t_{d1} = 10$ thousand hours—the period of ER revision, comparable to one year of operation of the FOCL, and $t_{d2} = 100$ thousand hours—period comparable to the service life of storage of the optical cable;
- number of components—S;
- FOCL operation intensity coefficient—K_I;
- indicator of the availability of the product with the i-th component in the ER set—P_A;
- availability factor—K_A.

The calculation algorithm is the following:

- b_i is calculated as the average number of failures of components of the i-th type for one product during the estimated time t_d: $b_i = m_i \lambda_i t_d K_I$;
- the indicator of spare parts availability for a product P_A is set;
- the average indicator of the lack of ER components is calculated: $q_{iA} = (1 - P_A)/S$;
- using the known values of q_{iA} and b_i, the values of m_i (the number of elements or components in the ER) are determined.

Consider, as an example, the calculation of the ER of an optical cable in a lightning-protection cable (OCLC) for a communication line built using FOCL-OHL (overhead power line) technology. A FOCL, constructed using FOCL-OHL technology, consisting of OCLC, connecting cable joints, support and tension fittings, is considered as a whole, since data on the damageability of lightning protection cable on OHL with a rated voltage of 110, 220, 330 and 500 kV are known. From the point of view of reliability theory, one of the key components of a fiber-optic transmission system is the average length of the OCLC insert (1.5 km), which is used in damage repair technology. Initial data are given in Table 4. The calculation results for b_i, $m(t_{d1})$, $m(t_{d2})$, $l(t_{d1})$, $l(t_{d2})$ are given in Table 5, where b is the average number of failures during the estimated time; m—number of elements; t_{d1}—the period of revision of the spare set (comparable to one year of operation); t_{d2}—period comparable to service life; λ—failure rate of elements of the i-th type λ_i; l—optical cable insertion length (multiple of the average insertion length of 1.5 km). The average indicator of the product's lack of components in the spare parts kit according to the formula $q_{iA} = (1 - P_A)/S$, where S is the number of components.

Let us consider the time it takes to deliver an ER to the accident site. According to current regulations for the design, construction, and operation of FOCL, the standard average time for restoring the working condition of a FOCL is 10 hours. Based on expert estimates, restoring the working state of an FOCL using a temporary optical cable insert takes no more than 6 hours, so the standard time for delivering an ER is 4 hours. Assuming an average speed of 50 kilometers per hour on Russian roads, the distance between the accident site and the nearest ER storage base should not exceed 200 kilometers, and the distance between ER bases should not exceed 400 kilometers. As the service life of the equipment approaches its end (and, consequently, the failure rate increases), operational reliability can be ensured by locating ERs at amplification points, where the distance between storage bases is less than 150 km.

Table 4

Initial data for optimizing ER

Indicator	**Rated voltage of overhead power line (OHL), kV**			
	110	220	330	500
Accident density per 100 km per year	0.08	0.05	0.04	0.03
Normative time to repair t_r, hour	10	10	10	10
Coefficient of availability K_A (100 km)	0.99990	0.99994	0.99995	0.99996
Coefficient of availability K_A (1.5 km)	0.9999985-074	0.9999991-045	0.9999992-537	0.9999994-030
Time to failure T_0, hour	6699709	11166936	13399427	16750408
λ, $1/h \times 10^7$	1.4926	0.8955	0.7463	0.5970
t_{d1}, h	10 000			
t_{d2}, h	100 000			
S	1			
K_I	1 (24 hours per day)			
P_A	0.995			
q_A	0.005			

Table 5

Results of calculation of ER

Indicator	**Nominal voltage of overhead lines, kV**			
	110	220	330	500
λ, 1/h×10^7	1.4926	0.8955	0.7463	0.5970
$b(t_{d1})$	0.1	0.06	0.05	0.04
$b(t_{d2})$	1.0	0.6	0.5	0.4
$m(t_{d1})$	1	1	1	1
$l(t_{d1})$, km	1.5	1.5	1.5	1.5
$m(t_{d2})$	4	3	3	2
$l(t_{d2})$, km	6	4.5	4.5	3.0

8. Conclusion

Fiber optic cables are an essential part of the national information infrastructure, widely used in fixed communication networks, mobile networks, including the upcoming 5G, 6G, and 7G technologies [19, 20]. Optical fibers and optical cable are considered aging objects according to reliability theory. Scientists from both domestic and abroad have developed advanced models to predict their aging. Due to various factors, the accuracy of predicting the maximum service life for optical fiber and optical cable can be quite inaccurate. Cable manufacturers, however, typically provide a lower estimate for the service life.

With sufficient evidence, it has been shown that it is possible to maintain cable reliability beyond the specified service life by optimizing ER locations and, accordingly, reducing the time to repair in case of failures.

9. Results

Long-term observations of the parameters of the G.652 optical fiber in the backbone cable have shown that all average sample values of the attenuation coefficient (0.190–0.197) fall within the confidence interval of the mathematical expectation (0.184–0.202). It has also been shown that the average maximum value of polarization-mode dispersion reduced to a length of 1 km (0.235 ps/$\sqrt{km}$) is significantly lower than the normalized quantile (0.5 ps/$\sqrt{km}$). With this reduced polarization-mode dispersion value, the total polarization-mode dispersion over the entire observation area between Kadala and Skovorodino (1027.3 km) will not exceed 7.5 ps.

10. Discussion

When calculating the required emergency cable reserve in case of continued operation after the warranty period, it is necessary to take into account several factors. These include the number of identical components with the same time to failure, the intensity of failure flow, the audit periods compared to the warranty period, security indicators, and the intensity factor of fiber-optic communication line operation. The optimization of the calculation using a proposed algorithm allows us to ensure the specified availability coefficient of the communication line.

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Сохранение надежности сетей связи при продолжении эксплуатации оптических кабелей за пределами их гарантийного срока службы

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Аннотация. В настоящее время, все большее количество волоконно-оптических линий связи оказываются в ситуации, когда гарантированная производителем продолжительность эксплуатации кабеля достигает заданного срока службы, однако качественные показатели линии допускают продолжение ее работы. Продление срока реальной эксплуатации требует качественного учета, как текущего состояния всех составляющих, так и динамики основных показателей. В статье предлагается метод решения проблемы сохранения надежности сетей связи при продолжении эксплуатации оптических кабелей за пределами их гарантийного срока службы. Исследование случайных показателей коэффициента затухания и поляризационно-модовой дисперсии оптического волокна, подкрепленное реальными эксплуатационными данными фрагмента сети, показывает высокую временнýю стабильность коэффициента затухания и поляризационно-модовой дисперсии оптического волокна G.652. Данный вывод позволяет говорить о продолжении эксплуатации оптических кабелей за пределом гарантийного периода. Для анализа ключевой метрики — старения — используются математические модели, учитывающие физико-химические свойства кабелей и условия проводимых для них контрольных испытаний. На примере, актуальном для текущего состояния российских оптоволоконных сетей, расчитывается количество элементов аварийного запаса, необходимых для поддержания уровня надежности их эксплуатации. Также приводятся практические рекомендации по размещению аварийного запаса.

Ключевые слова: сети связи, волоконно-оптические кабели, срок службы, эксплуатационный показатель надежности