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A comprehensive framework for reliability assessment of optical fiber communication systems: From physical degradation mechanisms to network-level evaluation

Blanchard Kiese Ndiwulu [1,*], Joseph Ramazani Mukamba [2,*], God'el Kinyoka Kabalumuna [3] and Jean Marcel Mbikayi Mupanya [4]

[1] *Department of Computer Science, Institut Supérieur de Commerce de Matadi (ISC-Matadi), Matadi, Kongo Central, Democratic Republic of the Congo.*

[2] *Department of Electrical Engineering, Faculty of Engineering, Université Mapon, Kindu, Democratic Republic of the Congo.*

[3] *Department of Physics and Applied Sciences, Université Pédagogique National (UPN), Kinshasa, Democratic Republic of the Congo.*

[4] *Department of Computer Science, Institut Supérieur de Statistique de Kinshasa (ISS), Kinshasa, Democratic Republic of the Congo.*

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Abstract

This paper presents a comprehensive reliability assessment framework for optical fiber communication systems by integrating physical degradation analysis, reliability modeling approaches, and network-level performance evaluation. First, the major failure mechanisms affecting conventional and advanced optical fibers are systematically investigated, highlighting their impact on mechanical integrity and optical transmission quality. Then, various reliability assessment methodologies are reviewed and compared, including statistical models, stochastic degradation models, fracture mechanics-based approaches, environmental reliability models, and advanced monitoring techniques based on optical sensing and artificial intelligence. The proposed framework is applied to the Kongo Central optical fiber network as a practical case study. Conventional reliability models based on exponential and Weibull distributions are evaluated and compared with a Markov-based stochastic approach to analyze degradation evolution, failure probability, and long-term availability. The results demonstrate that the Weibull model provides a more realistic representation of aging-related degradation compared with the exponential model, while the Markov approach enables a detailed description of transitions between healthy, degraded, and failed states by incorporating maintenance effects. The analysis also shows that network reliability is strongly influenced by failure rates, repair duration, and the effectiveness of redundancy strategies. This study provides an integrated methodology for bridging physical failure mechanisms and system-level reliability evaluation, offering valuable insights for predictive maintenance, resilience improvement, and the design of future intelligent optical communication infrastructures.

Keywords: Optical fiber communication systems; Reliability assessment; Degradation mechanisms; Weibull model; Markov process; Fracture mechanics; Predictive maintenance; Network resilience

1. Introduction

The rapid expansion of digital infrastructures, data centers, 5G/6G communication networks, Internet of Things (IoT) applications, and industrial connected systems has significantly increased the reliance on optical fiber technologies as the primary transmission medium for modern communication networks. Due to their exceptional transmission capacity, low attenuation, large bandwidth, and immunity to electromagnetic interference, optical fibers have become

* Corresponding authors: Blanchard Kiese Ndiwulu and Joseph Ramazani Mukamba

the fundamental backbone of terrestrial, submarine, metropolitan, and industrial communication infrastructures [1], [2], [3]. However, the long-term availability and performance of these infrastructures strongly depend on the reliability of optical fibers and associated network components, which are continuously exposed to mechanical stresses, thermal variations, environmental constraints, material aging, and manufacturing or installation imperfections [4].

Reliability assessment of optical fiber communication systems has consequently become a critical research issue to guarantee the continuity of digital services and the operational stability of communication infrastructures. Unlike traditional transmission systems, modern optical networks are required to provide extremely high availability while supporting bandwidth-intensive applications and mission-critical services. Nevertheless, optical fibers remain vulnerable to various degradation mechanisms that may progressively affect transmission quality or lead to complete service interruption. These failures can occur either suddenly, such as accidental cable cuts and mechanical breaks, or progressively through the accumulation of physical degradation phenomena. Among the dominant mechanisms are static fatigue, stress corrosion, micro-bending losses, radiation-induced attenuation, thermal aging, and deterioration of polymer protective coatings [5]. Understanding these mechanisms is therefore essential for predicting fiber lifetime, improving network resilience, and developing efficient maintenance strategies.

Several studies have investigated the reliability of optical fiber systems using different modeling and evaluation approaches. Probabilistic and stochastic models, particularly Markov chains and semi-Markov processes, have been widely employed to represent the evolution of degradation states and estimate system availability under uncertain operating conditions [6], [7], [8], [9], [10]. These approaches allow the transition between different operational states, such as healthy, degraded, and failed conditions, to be mathematically characterized. In parallel, statistical reliability models based on probability distributions, including exponential, Weibull, and lognormal laws, have been extensively used to describe aging behaviors, estimate failure probabilities, and predict the lifetime of optical components [11], [12], [13]. Furthermore, mechanical reliability approaches based on fracture mechanics have provided important contributions to the understanding of crack initiation, crack propagation, and fatigue-induced rupture by establishing relationships between mechanical stresses and fiber failure probability [14], [15], [16].

In addition to conventional reliability modeling techniques, recent advances in optical sensing and monitoring technologies have significantly improved the capability to detect, locate, and predict optical network failures. Optical Time Domain Reflectometry (OTDR), Optical Frequency Domain Reflectometry (OFDR), Fiber Bragg Grating (FBG) sensors, and distributed optical sensing techniques have demonstrated significant potential for real-time condition monitoring, early anomaly detection, and degradation localization [17], [18], [19], [20]. Moreover, artificial intelligence (AI) and machine learning approaches are increasingly integrated into optical network supervision systems due to their ability to extract complex degradation patterns, predict abnormal behaviors, and estimate the remaining useful lifetime of optical components [20]. Furthermore, self-monitoring and self-healing optical network architectures based on redundancy mechanisms, intelligent optimization algorithms, and automated recovery strategies have emerged as promising solutions to improve the resilience and availability of future optical infrastructures [21], [22], [23], [24], [25].

Despite these significant developments, existing studies remain largely fragmented. Most contributions independently investigate specific aspects of optical fiber reliability, including physical degradation mechanisms, statistical lifetime prediction, fault diagnosis techniques, or artificial intelligence-based monitoring approaches. However, a comprehensive framework integrating physical failure mechanisms, reliability indicators, advanced evaluation methods, and practical network-level assessment is still insufficiently addressed. This limitation makes it difficult to establish a global understanding of the interactions between degradation phenomena and operational reliability, particularly for regional optical networks deployed under heterogeneous environmental and operational conditions.

To overcome this limitation, this paper presents a comprehensive reliability assessment study of optical fiber communication systems by combining failure mechanism analysis, reliability modeling approaches, and practical network evaluation. The objective is to establish an integrated framework capable of characterizing degradation phenomena, quantifying reliability performance, and supporting maintenance decision-making for optical infrastructures.

The main contributions of this paper are summarized as follows: (i) A comprehensive analysis of the major failure mechanisms affecting optical fibers, including mechanical, optical, thermal, environmental, radiative, and advanced fiber-specific degradation phenomena; (ii) A detailed review of reliability modeling and evaluation methodologies, including statistical models, stochastic processes, mechanical reliability approaches, monitoring-based techniques, and artificial intelligence-driven methods; (iii) A practical reliability assessment of the Kongo Central optical fiber network, used as a case study to evaluate reliability performance, identify critical degradation factors, and investigate possible strategies for improving network availability and resilience.

The proposed assessment framework is applied to the Kongo Central optical fiber network, which represents a regional communication infrastructure where service continuity is essential for supporting digital connectivity and socioeconomic development. The analysis focuses on the evaluation of reliability behavior through appropriate reliability indicators and failure models, providing insights into the long-term performance of optical links and the influence of degradation mechanisms on network operation. The obtained results contribute to identifying vulnerable network elements and defining effective maintenance and reliability enhancement strategies.

The remainder of this paper is organized as follows. Section II presents the major failure mechanisms of optical fibers, including mechanical, optical, environmental, thermal, radiation-induced, and advanced fiber-related degradation phenomena. Section III describes the main reliability modeling and evaluation methods, including statistical, stochastic, mechanical, monitoring-based, and artificial intelligence approaches. Section IV presents the reliability assessment results of the Kongo Central optical fiber network and discusses the obtained findings, limitations, and improvement strategies. Finally, Section V concludes the paper and provides future research perspectives

2. Major failure mechanisms of optical fibers

Despite their excellent transmission performance, optical fibers remain susceptible to a wide range of degradation mechanisms that progressively impair their mechanical integrity and optical performance throughout their service life. These degradation processes may eventually compromise the reliability of optical communication systems, distributed sensing networks, and high-power photonic devices. In general, fiber failures are classified into two broad categories: hard failures, which result in an abrupt interruption of signal transmission due to catastrophic fiber breakage, and soft failures, which are characterized by a gradual deterioration of optical performance without immediate service interruption. This distinction is particularly important in the context of predictive maintenance, where early detection of soft failures enables preventive interventions before catastrophic failure occurs [26].

The degradation of optical fibers originates from the combined effects of mechanical loading, environmental exposure, manufacturing imperfections, optical propagation phenomena, thermal stresses, ionizing radiation, and installation-related constraints. These mechanisms rarely act independently; instead, they interact synergistically, accelerating crack propagation, increasing optical attenuation, and ultimately shortening the operational lifetime of the fiber. Consequently, understanding the physical origin of each degradation mechanism constitutes a fundamental prerequisite for accurate reliability assessment and the development of effective predictive maintenance strategies.

2.1. Mechanical Failure Mechanisms

Mechanical degradation is one of the primary factors limiting the long-term reliability of optical fibers. Although silica possesses a high theoretical strength, manufacturing, handling, installation, and environmental exposure introduce microscopic surface and subsurface flaws that progressively propagate under mechanical loading, ultimately leading to catastrophic fracture.

Static fatigue is the dominant failure mechanism, resulting from the slow growth of pre-existing cracks under constant tensile stress through stress-corrosion reactions between water molecules and Si–O bonds. Fiber lifetime is therefore strongly dependent on both the applied stress and environmental humidity. Long-term aging further promotes surface degradation, while phenomena such as the *fatigue knee* and *crack pop-in* accelerate crack initiation and propagation under humid conditions [14], [15], [16]. Under cyclic loading, induced by vibrations, thermal cycling, or repeated bending, crack propagation is further accelerated, significantly reducing fiber lifetime compared with static loading, particularly in aerospace, offshore, and structural health monitoring applications [27].

Environmental conditions considerably amplify mechanical degradation. Humidity accelerates stress-corrosion reactions, whereas elevated temperature increases chemical reaction rates and thermo-mechanical aging, resulting in shorter failure times, especially in humid or submerged environments [14], [28]. The combined action of mechanical stress, moisture, and temperature therefore represents a major limitation for long-term deployment in harsh environments.

Mechanical reliability is also governed by intrinsic manufacturing defects, including microcracks, inclusions, impurities, air bubbles, and geometrical irregularities that act as stress concentration sites. Residual stresses generated during fiber drawing and high drawing speeds further promote crack initiation, while microstructured optical fibers (MOFs) exhibit additional vulnerability because their air-hole interfaces provide multiple crack initiation sites [14], [15].

Finally, the degradation of the polymer protective coating significantly reduces fiber durability. Coating damage during fabrication, installation, splicing, or connectorization may expose the silica surface to scratches, micro-notches, and bruises, accelerating fatigue failure. Moreover, thermal aging and chemical degradation of polymer coatings progressively reduce their elasticity and protective capability, increasing the susceptibility of the silica fiber to environmental attack and mechanical failure [29], [30], [31], [32].

2.2. Fiber Bending-Related Failures

Optical fiber bending is a major source of transmission degradation because it disrupts the confinement of light within the fiber core. Two principal mechanisms are distinguished: macro-bending and micro-bending [4].

Macro-bending occurs when the bending radius falls below the critical value, allowing guided modes to leak into the cladding and radiate outward, thereby increasing attenuation. The resulting power loss strongly depends on the bending radius. In addition, coupling between guided modes and whispering-gallery modes may produce oscillatory loss behavior [33]. In high-power optical systems, radiated energy absorbed by the polymer coating can initiate thermal runaway, leading to coating degradation, permanent glass deformation, and ultimately transmission failure [34].

Micro-bending arises from microscopic deformations caused by cabling, winding, compression, or localized mechanical stresses. These small-scale perturbations induce coupling between guided and radiation modes through local variations in the effective refractive index, resulting in increased attenuation and reduced signal-to-noise ratio [35]. The phenomenon is particularly critical in composite-embedded fibers and hollow-core fibers, where mechanical stresses and geometric imperfections significantly increase leakage losses and degrade transmission performance [4], [29].

2.3. Optical Failures

Optical failures progressively degrade signal quality and limit the transmission performance of optical fibers. The principal mechanisms include absorption, scattering, dispersion, polarization mode dispersion (PMD), and connector or splice losses, all of which reduce the optical power budget and impair communication reliability.

Absorption losses arise from the conversion of optical energy into heat through intrinsic silica absorption and extrinsic impurities such as hydroxyl (OH^-) ions, transition metals, and fabrication contaminants. Hydrogen diffusion in harsh environments further promotes hydroxyl formation, increasing attenuation and reducing fiber lifetime [4], [36]. Light scattering also contributes significantly to attenuation. Rayleigh scattering is the dominant intrinsic mechanism in conventional silica fibers, whereas nonlinear scattering at high optical powers and surface roughness in microstructured and hollow-core fibers introduce additional transmission losses [4], [37].

Another major limitation is dispersion, which broadens optical pulses during propagation. Chromatic dispersion results from the wavelength dependence of the refractive index, while modal dispersion in multimode fibers arises from different propagation paths, leading to inter-symbol interference (ISI) over long transmission distances [4]. Similarly, Polarization Mode Dispersion (PMD), caused by birefringence induced by manufacturing imperfections, residual stresses, and external mechanical loading, generates differential group delay, pulse distortion, and increased bit error rates in high-speed optical communication systems [26].

Connector and splice losses introduce additional insertion losses due to lateral, angular, or longitudinal misalignment between interconnected fibers. The accumulation of connectors, splices, and repair operations progressively reduces the available optical power margin, accelerating network degradation and shortening the operational lifetime of optical communication systems [38], [39], [40].

2.4. Ionizing Radiation-Induced Failures

Optical fibers operating in space, nuclear, medical, and defense environments are continuously exposed to ionizing radiation such as X-rays, γ-rays, neutrons, protons, and heavy ions. These radiations induce ionization and atomic displacement within the silica network, progressively degrading both the optical and mechanical properties of the fiber and thereby reducing its long-term reliability [41].

The dominant degradation mechanism is Radiation-Induced Attenuation (RIA), which results from the formation of radiation-generated absorbing defect centers in silica. These defects increase optical absorption at telecommunication wavelengths, leading to progressive transmission losses. The severity of RIA depends on the accumulated dose, radiation type, fiber composition, and operating wavelength, and may ultimately cause communication or sensing failure [41], [42].

Ionizing radiation also generates point defects by breaking chemical bonds and trapping electrons and holes, producing color centers that introduce additional absorption bands. Germanium-doped fibers are generally more radiation-sensitive than pure-silica-core fibers because they contain a higher concentration of defect precursors [41], [42]. In addition, high-energy particles, particularly neutrons, produce atomic displacement damage, creating vacancies and defect clusters that modify the silica structure, locally alter the refractive index, and further increase transmission losses [41].

Another important effect is the Radiation-Induced Refractive Index Change (RIRIC), caused by radiation-induced atomic defects that modify the material polarizability. These refractive-index variations affect light propagation, induce modal perturbations, and degrade the accuracy of fiber Bragg grating (FBG) and interferometric sensors, which rely on stable optical properties [42]. Hydrogen plays a dual role in radiation damage. While hydrogen diffusion promotes hydroxyl (OH) formation and increases optical absorption, it can also passivate radiation-induced color centers, thereby reducing attenuation and improving the radiation resistance of optical fibers deployed in harsh environments [32], [36], [42].

2.5. Failures Specific to Advanced Optical Fibers

Advanced optical fibers provide enhanced transmission and sensing capabilities for telecommunications, nonlinear photonics, and harsh-environment applications. However, their complex architectures introduce specific mechanical and optical degradation mechanisms that differ from those of conventional silica fibers.

Microstructured Optical Fibers (MOFs) are characterized by arrays of air holes that enable precise dispersion control and high sensing performance. Nevertheless, the numerous air glass interfaces act as preferential crack initiation sites, reducing mechanical strength. In addition, moisture penetration into the air channels promotes hydroxyl (OH) formation, increasing absorption losses and accelerating optical aging. Their reliability is therefore highly dependent on manufacturing quality and drawing conditions, which determine the internal stress distribution and microstructure geometry [15], [45].

Hollow-Core Fibers (HCFs) guide light mainly through air, minimizing material absorption and nonlinear effects. However, they are highly sensitive to geometric imperfections that increase confinement losses under bending or structural deformation. Surface roughness at the air–glass interfaces also enhances scattering losses, while dimensional variations in advanced structures such as Nested Antiresonant Nodeless Fibers (NANFs) can significantly degrade transmission performance [37].

Fiber Bragg Grating (FBG) sensors exhibit additional reliability issues associated with the grating inscription process. Laser inscription may introduce microvoids and structural defects that reduce the mechanical strength of the fiber, with Type II femtosecond-written gratings showing lower fatigue resistance than pristine fibers. Furthermore, the local removal of the protective polymer coating before grating fabrication exposes the silica surface to mechanical and chemical attack, promoting microcrack initiation and reducing the long-term reliability of FBG-based sensing systems [30].

3. Reliability modeling and evaluation methods

Reliability assessment of optical fiber systems requires advanced modeling approaches capable of capturing degradation mechanisms, random failures, environmental effects, and maintenance processes. Mathematical models are essential to predict failure probability, degradation evolution, and residual lifetime beyond experimental observations. Different approaches, including stochastic, statistical, mechanical, environmental, and data-driven methods, provide complementary tools for evaluating fiber reliability. Their integration enables accurate performance prediction, optimized maintenance strategies, and improved long-term availability of optical communication systems.

3.1. Stochastic Reliability Modeling

Stochastic models provide an effective framework for representing the time-dependent reliability degradation of optical fiber systems by considering random failure events, aging mechanisms, and maintenance actions. Among these approaches, Markov and semi-Markov models are widely used to describe the evolution of fiber reliability through successive degradation states associated with progressive transmission quality degradation and increasing unavailability rates [7], [8].

In a Markov degradation model, the optical fiber lifetime is represented by a set of discrete degradation states D_i, where each state corresponds to a specific aging level characterized by increased optical attenuation and reduced transmission performance. The unavailability coefficient associated with each degradation state is expressed in equation (1), where

λ_i represents the failure rate associated with degradation state D_i, and μ denotes the repair rate. This model highlights that system availability depends on the balance between failure occurrence and restoration capability. As aging progresses, the failure rate increases, leading to a progressive reduction in operational availability [7].

$$K_{ni} = \frac{\lambda_i}{\lambda_i + \mu} \tag{1}$$

However, classical Markov models assume exponentially distributed residence times in each state, which may not accurately represent optical fibers subjected simultaneously to progressive aging and sudden accidental failures. Therefore, semi-Markov processes are introduced to incorporate both slow degradation mechanisms and abrupt failures caused by mechanical stress, excavation activities, or environmental hazards [8]. The probability of remaining operational until the next inspection period is expressed in equation (2), where T_{TP} is the inspection interval, λ is the sudden failure rate, and α represents the probability of diagnostic error. This formulation demonstrates the significant influence of monitoring accuracy on global reliability, since diagnostic errors may lead to inappropriate maintenance decisions and inaccurate lifetime estimation.

$$p_{TP} = (1-\alpha)e^{-\lambda T_{TP}} \tag{2}$$

The progressive degradation of optical fibers is mainly characterized by an increase in attenuation. The cumulative attenuation after successive degradation cycles and repair operations can be modeled as in equation (3), where b_i denotes the average attenuation at degradation state i, Δb is the natural attenuation increase caused by aging, η\etaη represents the additional degradation induced by repairs, and qD is the recovery probability after sudden failure. When $\eta > 1$, repeated repair operations accelerate the global aging process due to additional losses introduced at splice points [9].

$$b_{i+1} = b_i + \Delta b + \eta\, \Delta b\, qD \tag{3}$$

The degradation process terminates when attenuation reaches a critical threshold beyond which transmission performance becomes unacceptable. The critical degradation level can be estimated from equation (4), where n is the total number of degradation states, m represents the number of inspection periods, and T_D corresponds to the average duration of a degradation state. This approach enables prediction of the optimal replacement time before service interruption occurs [9].

$$I \geq \frac{1 + \eta\left[1-(1-\alpha)^m e^{-\lambda T_D}\right]}{n} \tag{4}$$

The mean operating lifetime, commonly expressed as Mean Time Between Failures (MTBF), is another important reliability indicator. For semi-Markov models, it is obtained as in equation (5), where m_{TP} represents the average number of operational periods. The lifetime increases when the transition probability without failure approaches unity, whereas higher failure rates significantly reduce the service duration [9].

$$t_D = m_{TP}\, T_{TP} = \frac{1-{p_{TP}}^m}{1-p_{TP}}\, T_{TP} \tag{5}$$

Beyond lifetime prediction, Markov models allow the evaluation of global availability by considering normal operation, degraded states, failures, and repair conditions. The availability coefficient is calculated from stationary state probabilities as in equation (6), where π_i denotes the stationary probability of state iii, and ν_i represents the average residence time in this state. This approach integrates failure mechanisms, maintenance actions, inspection strategies, and diagnostic uncertainties into a unified reliability evaluation framework [10].

$$K_A(T) = \sum_{i=1} \pi_i\, \nu_i \tag{6}$$

3.2. Statistical Reliability Modeling of Optical Fiber Communication Systems

Statistical reliability models provide a quantitative framework for evaluating the failure probability of optical communication systems. Unlike stochastic degradation models, statistical approaches characterize component failure behavior using probability distributions associated with physical aging mechanisms. The most commonly adopted models include the exponential distribution for random failures, the Weibull distribution for aging phenomena, and software reliability growth models such as Musa–Okumoto. These approaches enable the estimation of individual component reliability and the evaluation of the overall system reliability.

3.3. Exponential Reliability Model

The exponential distribution is widely used to model components operating during their useful lifetime, where the failure rate is assumed to be constant. The reliability function of an optical transceiver can be expressed in equation (7), where $P_{tr}(t)$ denotes the probability that the transceiver operates without failure up to time$t$, and λ_{tr} represents the constant failure rate. The corresponding probability density function is given in equation (8), while the instantaneous failure rate (hazard rate) remains constant : $h(t) = \lambda_{tr}$. This its simplicity, making it suitable for electronic components whose failures are mainly random and independent of aging effects [11].

$$P_{tr}(t) = e^{-\lambda_{tr}} \quad (7)$$

$$f(t) = \lambda_{tr}\, e^{-\lambda_{tr}} \quad (8)$$

3.4. Weibull Model for Aging and Mechanical Degradation

Unlike electronic components, optical fibers, optical amplifiers, and connectors experience progressive degradation caused by mechanical stress, micro-crack propagation, environmental effects, and stress corrosion. Therefore, the Weibull distribution is widely adopted to represent time-dependent failure mechanisms. The reliability function is defined as in equation (9), where α is the shape parameter and β is the scale parameter corresponding to the characteristic lifetime.

$$P_{ch}(t) = e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \quad (9)$$

The shape parameter provides important physical information regarding the failure mechanism:

$\alpha < 1$: early failures dominate due to manufacturing defects;

$\alpha = 1$: the Weibull distribution becomes equivalent to the exponential model;

$\alpha > 1$: failures are mainly associated with aging and degradation.

For optical fibers subjected to mechanical loading, values of $\alpha > 1$ are commonly observed, indicating an increasing failure rate caused by long-term degradation [12]. The associated hazard function is expressed as in equation (10), which allows the representation of accelerated aging effects observed in optical components.

$$h(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1} \quad (10)$$

3.5. Weibull Parameter Estimation for Optical Connectors

Optical connectors are among the most vulnerable components due to mechanical vibration and environmental stresses. Their reliability is generally evaluated through insertion loss (IL) variation measurements during accelerated vibration tests.

The Weibull parameters are estimated from the applied mechanical stresses, including maximum and minimum stress levels (σ_1 and σ_2), allowing the correlation between mechanical loading and failure probability to be established [13]. Standardized GR-326 testing procedures apply random vibration excitation of 2.306 $Grms$ for 6 hours to evaluate connector stability after mechanical aging. The Weibull model enables lifetime prediction under different operating conditions and provides an effective tool for reliability assessment of optical interconnection systems.

3.6. Musa–Okumoto Software Reliability Growth Model

The reliability of optical communication systems is not limited to hardware components. Software failures associated with network management, monitoring systems, and control platforms may also generate service interruptions. The Musa–Okumoto logarithmic model is commonly employed to describe software fault reduction during the testing and validation phases. The cumulative number of detected failures is expressed in equation (11), where λ_0 represents the initial failure intensity and θ denotes the fault removal parameter.

$$m(t) = \frac{1}{\theta}\ln(1 + \lambda_0\ \theta t\ ) \tag{11}$$

This model is based on a non-homogeneous Poisson process, where the failure rate decreases progressively as software defects are identified and corrected. Its integration is particularly relevant for modern optical networks based on SDN architectures, DWDM systems, and intelligent supervision platforms incorporating artificial intelligence techniques.

3.7. Overall Reliability of Optical Transmission Systems

Optical transmission systems are generally composed of multiple components connected in series, including transceivers, optical channels, amplifiers, and control software. In such architectures, the failure of a single element may interrupt the entire communication link.

The global reliability can be approximated as in equation (12), where $P_{tr}(t)$, $P_{ch}(t)$, $P_{amp}(t)$ and $P_{SW}(t)$ represent respectively the reliability of the transceiver, optical channel, optical amplifier, and software control system.

$$P_{syst}(t) = P_{tr}(t) + P_{ch}(t) + P_{amp}(t) + P_{SW}(t) \tag{12}$$

This relationship highlights that system reliability decreases as the number of serial components increases. Consequently, even highly reliable individual components may lead to reduced global availability when integrated into complex optical networks. This limitation motivates the use of redundancy strategies in long-haul optical communication systems.

3.8. Failure Probability Density Function

The probability density function describes the likelihood of failure occurrence at a specific time instant. It is defined as in equation (13), where $F(t)$ represents the cumulative failure distribution and $P(t)$ denotes the reliability function.

$$f(t) = \frac{d\,F(t)}{dt} = -\frac{d\,P(t)}{dt} \tag{13}$$

For optical communication systems combining electronic components, optical fibers, amplifiers, and software elements, the global failure density can be expressed by combining exponential, Weibull, and Musa–Okumoto contributions:

$$f(t) = P_{syst}(t)\left[\lambda_{tr} + \frac{\alpha_{ch}}{\beta_{ch}}\ \left(\frac{t}{\beta_{ch}}\right)^{\alpha_{ch}} + \frac{\alpha_{amp}}{\beta_{amp}}\ \left(\frac{t}{\beta_{amp}}\right)^{\alpha_{amp}-1} + \frac{\lambda_O}{\lambda_O + \theta\ t\ \lambda_O}\right] \tag{14}$$

This formulation integrates different failure mechanisms into a unified reliability framework [12]. The resulting failure density function provides a valuable indicator for preventive maintenance scheduling, risk assessment, and optimization of replacement strategies. It also enables the identification of critical components contributing most significantly to the overall system failure probability.

3.9. Mechanical Fatigue and Fracture Modeling of Optical Fibers

The long-term mechanical reliability of optical fibers is primarily governed by the initiation and propagation of surface micro cracks in the silica glass. These defects, introduced during manufacturing, handling, or installation, progressively grow under sustained mechanical loading and environmental exposure until catastrophic failure occurs. Consequently, mechanical reliability models aim to describe crack propagation mechanisms, predict the service lifetime of optical fibers, and evaluate their residual strength under various operating conditions[16]..

The propagation of surface cracks is commonly described using Linear Elastic Fracture Mechanics (LEFM). The stress intensity factor K_I characterizes the stress field at the crack tip and depends on the applied stress, crack geometry, and crack size. It is expressed in equation (15), where Y is the geometric correction factor, σa is the applied tensile stress, and c denotes the half-length of the surface crack. As the crack length or applied stress increases, K_I also increases. Catastrophic fracture occurs when K_I reaches the critical fracture toughness K_{IC}, explaining why even micrometer-sized surface flaws can ultimately lead to fiber failure [16].

$$K_I = Y\sigma a\sqrt{\pi c} \tag{15}$$

Before catastrophic rupture, silica fibers generally experience subcritical crack growth caused by stress corrosion. Water molecules react with strained Si–O bonds at the crack tip, accelerating crack propagation. The crack growth rate is commonly represented by the power-law model in equation (16), where A is a material-dependent constant and n is the stress-corrosion coefficient. For standard silica optical fibers, experimental studies typically report $n \approx 20$, indicating that even small increases in mechanical stress can significantly accelerate crack growth and aging.

$$v = \frac{dc}{dt} = A\,{K_I}^n \tag{16}$$

By integrating the crack growth law under constant applied stress, the static lifetime of the fiber can be estimated as in equation (17), where t_f is the failure time, B is a material constant, σ_i is the initial fiber strength, and σ_a is the applied stress. This relationship highlights the strong nonlinear dependence of service lifetime on mechanical loading and is widely employed in the design of terrestrial, aerial, and submarine optical cable systems.

$$t_f = B\sigma_i^{n-2}\sigma_a^{-n} \tag{17}$$

Although the power-law model is extensively used, it may overestimate long-term lifetime during multi-decade extrapolations. To address this limitation, an exponential crack growth model has been proposed as in equation (18), where A_1 and n_1 are experimentally determined constants. This formulation generally provides more conservative lifetime predictions and better reproduces the long-term degradation observed in aged optical fibers, particularly in high-reliability submarine communication systems.

$$\frac{dc}{dt} = A_1 e^{\,n_1 K_I} \tag{18}$$

Mechanical reliability is further enhanced through proof testing, during which each optical fiber is briefly subjected to a proof stress σ_p higher than the expected service stress. Fibers containing critical flaws fail during the test, while the remaining fibers satisfy $\sigma_i > \sigma_p$. This screening process truncates the initial defect distribution and significantly improves the initial reliability of optical communication networks.

To statistically characterize the remaining defects, Weibull distributions are commonly employed. Because optical fibers usually contain both manufacturing-induced defects and intrinsic microscopic surface flaws, a bimodal Weibull model provides improved lifetime prediction. The failure probability is expressed in equation (19), where L is the fiber length, L_0 is the reference length, σ_o is the characteristic stress, and mmm is the Weibull modulus. Experimental studies report $m = 3 - 5$ for large manufacturing defects and $m = 20 - 30$ for intrinsic surface flaws, leading to significantly improved long-term reliability assessment [54].

$$P(\sigma, L) = 1 - \exp\left[-\frac{L}{L_0}\left(\frac{\sigma}{\sigma_o}\right)^m\right] \tag{19}$$

Finally, modern reliability models also account for the Pop-in phenomenon, in which new radial surface cracks can spontaneously form in humid environments even under relatively low mechanical stress. These moisture-induced cracks may develop after proof testing, causing unexpected failures several years after installation. Incorporating the Pop-in mechanism therefore improves the accuracy of long-term mechanical reliability predictions for silica optical fibers [16].

3.10. Environmental and Physicochemical Reliability Modeling

Environmental conditions significantly influence the long-term reliability of optical fibers, particularly in harsh environments such as nuclear facilities, offshore installations, oil wells, and space applications. Environmental reliability modeling aims to quantify the effects of multiple degradation factors in order to predict performance evolution and optimize maintenance strategies. Since optical components are simultaneously exposed to temperature, humidity, mechanical vibrations, and electromagnetic disturbances, multifactorial models provide a more realistic description of degradation than independent single-factor approaches [46].

A commonly adopted multifactor regression model expresses the output optical power as in equation (20), where $T(t)$ is the temperature, $H(t)$ is the relative humidity, $E(t)$ denotes the electromagnetic field intensity, $M(t)$ represents mechanical vibrations, γ_i are regression coefficients, and $\varepsilon(t)$ is the random error. This formulation captures the coupled effects of environmental variables and facilitates the identification of critical operating conditions affecting optical system reliability [46].

$$P_{out}\,(t) = \gamma_0 + \gamma_1\,T(t) + \gamma_2\,H(t) + \gamma_3\,E(t) + \gamma_4\,M(t) + \gamma_5\,T(t)\,H(t) + \varepsilon(t) \tag{20}$$

The relative contribution of each environmental parameter can be quantified through a normalized sensitivity coefficient defined in equation (21), where X_i represents the environmental variable under investigation and Y denotes the selected reliability indicator. Experimental analyses indicate that temperature and humidity account for the largest share of long-term reliability degradation, making them the dominant factors in preventive maintenance planning.

$$S_i = \frac{\partial Y}{\partial X_i}\,\frac{\partial X_i}{\partial Y} \tag{21}$$

Environmental degradation models are frequently integrated with stochastic reliability frameworks to support predictive maintenance. Maintenance actions are typically initiated when the estimated reliability falls below a predefined threshold ($R(t) \leq 0.9$), thereby reducing the probability of unexpected failures and improving service continuity in optical communication networks [46].

3.11. Advanced Reliability Assessment Methods for Optical Fiber Systems

The reliability assessment of optical fiber communication systems has evolved beyond conventional statistical and mechanical models. The increasing complexity of high-capacity optical networks, smart infrastructures, and distributed sensing systems has driven the development of advanced techniques capable of early degradation detection, accurate fault localization, and remaining useful life prediction. These approaches combine optical reflectometry, numerical modeling, probabilistic simulations, Digital Twins, and artificial intelligence to enable continuous health monitoring and predictive maintenance of optical infrastructures [48], [49].

Among diagnostic techniques, Optical Time Domain Reflectometry (OTDR) remains the most widely adopted method for fault localization. It operates by injecting an optical pulse into the fiber and analyzing the Rayleigh backscattered signal to identify localized losses, defective splices, macro-bending events, and fiber breaks. Owing to its high spatial resolution, OTDR can accurately locate defects over transmission distances of several tens of kilometers, thereby significantly improving maintenance efficiency [50].

Progressive degradation can also be detected by reconstructing the longitudinal attenuation profile of the fiber. In coherent optical communication systems, this reconstruction relies on the inversion of the nonlinear Schrödinger equation (NLSE), expressed in equation (22), where $A(z,t)$ is the complex optical field amplitude, $\alpha(z)$ is the local attenuation coefficient, β_2 is the chromatic dispersion parameter, and γ is the nonlinear coefficient. Solving the inverse problem provides a continuous attenuation map, enabling early identification of degradation zones before critical failures occur [48].

$$\frac{\partial\,A(z,t)}{\partial z} = -\frac{\alpha(z)}{2}A + i\frac{\beta_2}{2}\,\frac{\partial^2 A}{\partial t^2} - i\,\gamma\,|A|^2 A \tag{22}$$

When analytical reliability evaluation is impractical, Monte Carlo simulation offers an efficient probabilistic framework by generating a large number of random failure scenarios. The system reliability is estimated in equation (23), where N_s is the number of successful simulations and N is the total number of simulated scenarios. This approach effectively captures the interactions among multiple failure mechanisms and is widely used to evaluate the resilience of optical networks exposed to natural hazards or multiple simultaneous link failures [51].

$$R = \frac{N_s}{N} \tag{23}$$

For redundant optical communication and distributed sensing networks, reliability can be quantified through a probabilistic robustness index in equation (24), where $P(S_k)$ is the probability of network state k, G_k is the average coverage capability, and $Var\,(C_k)$ denotes the performance variance. This metric enables quantitative comparison of redundant architectures and supports reliability-oriented network design [52].

$$R = \sum_k P\,(S_k)\frac{G_k}{1 + Var\,(C_k)} \tag{24}$$

The Bit Error Rate (BER) remains one of the most representative indicators of transmission reliability. It is defined in equation (25), where N_e is the number of erroneous bits and N_b is the total number of transmitted bits. A gradual increase in BER generally indicates signal degradation caused by attenuation, chromatic dispersion, or nonlinear impairments. Modern monitoring systems continuously supervise BER using finite-state machines (FSMs) and trigger maintenance when predefined thresholds or Forward Error Correction (FEC) limits are exceeded [49].

$$BER = \frac{N_e}{N_b} \quad (25)$$

In addition to BER, several optical performance indicators are routinely employed for experimental reliability assessment, including fiber attenuation, Optical Signal-to-Noise Ratio (OSNR), Polarization Mode Dispersion (PMD), macro-bending losses, and connector insertion losses. The combined analysis of these parameters enables early identification of degradation mechanisms and supports predictive maintenance strategies that improve network availability while reducing operational costs [49], [48].

Recently, Artificial Intelligence (AI) has become a key technology for optical network reliability assessment. The large amount of data generated by OTDR, Optical Frequency Domain Reflectometry (OFDR), and distributed optical sensors has enabled the application of Machine Learning (ML) and Deep Learning (DL) algorithms for automated fault diagnosis. Unlike conventional threshold-based or analytical approaches, AI techniques learn complex relationships directly from measurement data to detect anomalies, localize faults, classify degradation mechanisms, and predict their future evolution. Consequently, AI-based reliability assessment has become an essential component of predictive maintenance frameworks for next-generation intelligent optical communication networks [49], [50], [53].

4. Results and discussion

This section presents the reliability assessment of the Kongo Central optical fiber network using the two modeling approaches : the conventional approach and the advanced approach. The conventional approach relies on analytical reliability models, including the exponential model, the Weibull model**,** th**e** redundancy model, and the Weibull-based failure rate model, whereas the advanced approach is based on Markov stochastic modeling. The analysis was performed using the network parameters described in Section II together with predefined operating assumptions. Furthermore, a comparative analysis between the Marko**v** and Monte Carlo methods is conducted to evaluate their accuracy, applicability, and limitations for the considered optical fiber network.

4.1. Conventional Reliability Approach

The conventional reliability assessment considers two representative operating scenarios derived from operational failure and repair data collected from the Kongo Central optical fiber network operator. The first scenario represents the worst-case operating condition, characterized by a 35% annual failure rate (35 failures/year/km) and an average repair time of 48 h**.** The second scenario corresponds to an improved operating condition, with a reduced annual failure rate of 20% (28 failures/year/km) and an average repair time of 4.5 h. In both cases, a Weibull shape parameter of β = 2 and a characteristic lifetime of 40 years were adopted. These assumptions are justified by the predominance of wear-out degradation mechanisms during network operation and by manufacturers' specifications corroborated by field experience. The two scenarios provide lower and upper reliability bounds, allowing a comprehensive evaluation of network performance under adverse and improved operating conditions.

Scenario 1: Failure Rate = 35% and Repair Time = 48 h

4.2. Exponential and Weibull Reliability Models

Figure 1 compares the reliability predictions obtained using the exponential and Weibull models under the worst-case operating scenario. The exponential model predicts a very rapid degradation of network reliability. As expected, the reliability is initially equal to unity, R(0) = 1**,** indicating a fault-free initial condition. However, the survival probability decreases sharply during the first year and rapidly approaches zero over the simulated period. This behavior results from the assumption of a constant and relatively high failure rate, leading to frequent early failures and a very limited expected service life. Consequently, the exponential model predicts poor long-term reliability under severe operating conditions.

In contrast, the Weibull model exhibits a significantly slower reliability degradation. Although $R(0) = 1$, the reliability decreases progressively throughout the observation period. Between 0 and 5 years, the reduction remains limited, while the reliability is still greater than 0.94 after 10 years, indicating a high probability of survival. The smooth evolution of the reliability curve reflects a gradual degradation process associated with material aging and wear mechanisms. This behavior is consistent with the time-dependent failure rate represented by the Weibull distribution ($\beta = 2$) and provides a more realistic description of the long-term mechanical degradation of underground optical fibers.

Overall, the results demonstrate that the Weibull model provides a more representative reliability prediction than the exponential model for underground optical fiber systems, since it captures the progressive deterioration of the fiber rather than assuming a constant failure rate. This observation is consistent with previous reliability studies on optical fiber aging and wear mechanisms.

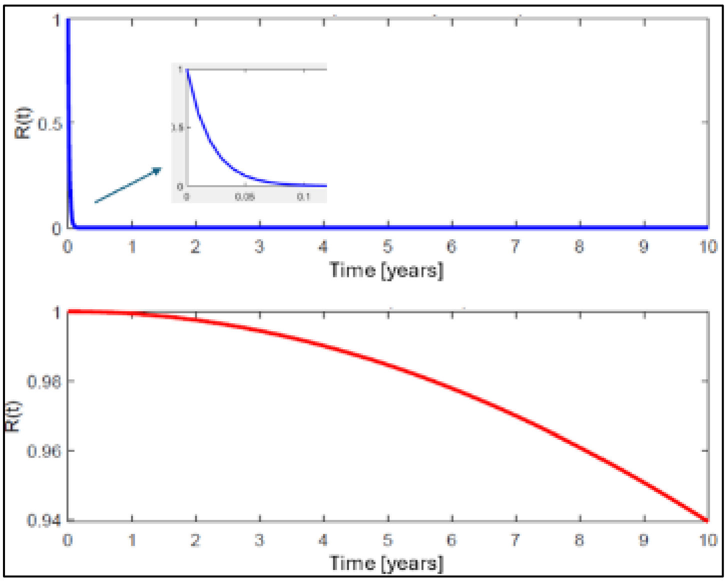

Figure 1 Simulation results of the optical fiber reliability analysis using the exponential model (blue curve), representative of a constant failure rate process, and the Weibull model (red curve), characterizing a progressive degradation mechanism

4.3. Reliability with Redundancy

Figure 2 illustrates the reliability evolution over time for the worst-case scenario (35% failure rate and 48 h repair time). The first subplot compares the exponential and Weibull reliability models, whereas the second subplot evaluates the impact of redundancy on the optical fiber network reliability. The comparison confirms the significant differences between the two reliability models. The exponential model predicts a rapid decrease in reliability, indicating a highly vulnerable optical fiber system under the assumed operating conditions. In contrast, the Weibull model exhibits a gradual degradation process, resulting in a substantially higher survival probability over the same time horizon. While the exponential model predicts an almost zero probability of survival after a relatively short operating period, the Weibull model maintains a high level of reliability, reflecting the progressive aging behavior of the fiber.

The simulation results also highlight the influence of system redundancy on network reliability. Although redundancy is generally introduced to improve system availability by providing alternative transmission paths or backup components, the obtained results (black curve) indicate only a limited reliability improvement under the considered conditions. The network remains susceptible to early failures, and the increase in survival probability is insufficient to significantly modify the overall degradation trend. This limited benefit can be attributed to the relatively high failure rate of individual components and the restricted effectiveness of the adopted redundancy architecture.

Overall, the results demonstrate that the selection of the reliability model strongly influences the predicted system performance. The exponential model provides a conservative estimate, whereas the Weibull model more accurately represents the time-dependent degradation behavior of underground optical fibers. Furthermore, the redundancy analysis shows that its effectiveness is highly dependent on the intrinsic reliability of individual components and the network architecture. These findings emphasize the importance of accurate reliability modeling for maintenance planning and the design of more reliable optical fiber communication networks.

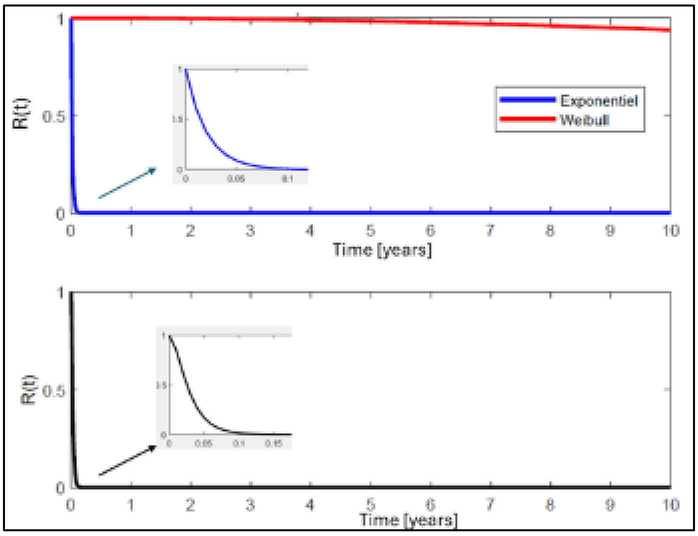

Figure 2 Reliability evolution as a function of time (expressed in years). The first subplot presents a comparison between the exponential and Weibull models, while the second highlights the reliability behavior of the optical fiber system in the presence of redundancy

4.4. Weibull Failure Rate Analysis

Figure 3 presents the evolution of the Weibull failure rate under the worst-case operating scenario (35% failure rate and 48 h repair time). The results show an increasing and approximately linear trend over the 10 year observation period. Initially, the failure rate remains close to zero ($\lambda(0) \approx 0$), indicating a low probability of instantaneous failure during the early operational stage. However, as time increases, $\lambda(t)$ continuously rises and reaches values between 0.012 and 0.014 at $t = 10$ years, revealing a progressive increase in failure risk.

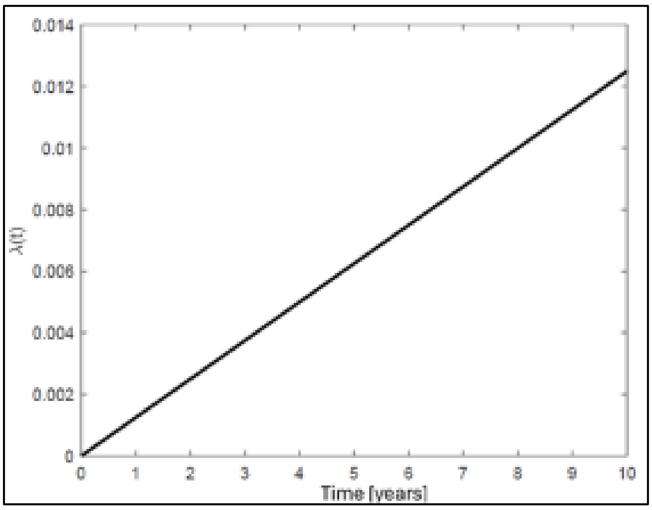

Figure 3 Evolution of the instantaneous failure rate as a function of time, within the framework of a Weibull distribution-based modeling approach

Scenario 2: Failure Rate = 20% and Repair Time = 4.5 h

This behavior indicates that the optical fiber degradation process is mainly governed by wear-out mechanisms. During the early lifetime period, the fiber exhibits high reliability due to the limited presence of degradation effects. Nevertheless, aging phenomena, repeated mechanical stresses, and progressive material deterioration gradually increase the likelihood of failure. Such an increasing failure rate is consistent with the typical behavior of aged components subjected to fatigue and long-term operational stresses.

The obtained results confirm the suitability of the Weibull model for representing age-dependent reliability degradation in optical fiber systems. The continuous increase in the failure rate provides valuable information for predicting future failures and developing preventive maintenance strategies. Therefore, Weibull-based reliability analysis can contribute to improving the availability, operational lifetime, and maintenance planning of optical communication infrastructures.

4.5. Exponential and Weibull Reliability Models

Figure 4 presents the reliability results obtained under improved operating conditions, considering a reduced failure rate of 28 failures/year/km (20%) and an average repair time of 4.5 h. Compared with the previous scenario, the overall reliability behavior remains similar; however, a slight improvement is observed, particularly for the exponential model.

Indeed, the exponential reliability model predicts a faster degradation compared with the Weibull model, but the reliability reaches zero after approximately 0.15 years, whereas in the previous case this limit was reached around 0.1 years (Figure 1). This difference highlights the influence of reduced failure frequency and shorter repair duration on the predicted system lifetime.

Conversely, the Weibull model maintains a behavior similar to that observed in the first scenario, characterized by a gradual and continuous decrease in reliability. This confirms that the Weibull distribution better captures the progressive aging and degradation mechanisms affecting optical fibers.

These results emphasize the importance of selecting an appropriate probabilistic model for reliability assessment. While the exponential model provides a simple analytical representation based on a constant failure rate, the Weibull model offers a more realistic description of time-dependent degradation phenomena. Therefore, Weibull-based modeling appears more suitable for long-term reliability prediction of optical fiber networks subjected to aging and wear mechanisms.

4.6. Reliability with Redundancy

Figure 5 presents the reliability performance with redundancy under improved operating conditions, considering a 20% failure rate and an average repair time of 4.5 h. The results highlight the sensitivity of system reliability to both the annual number of failures and the associated repair duration.

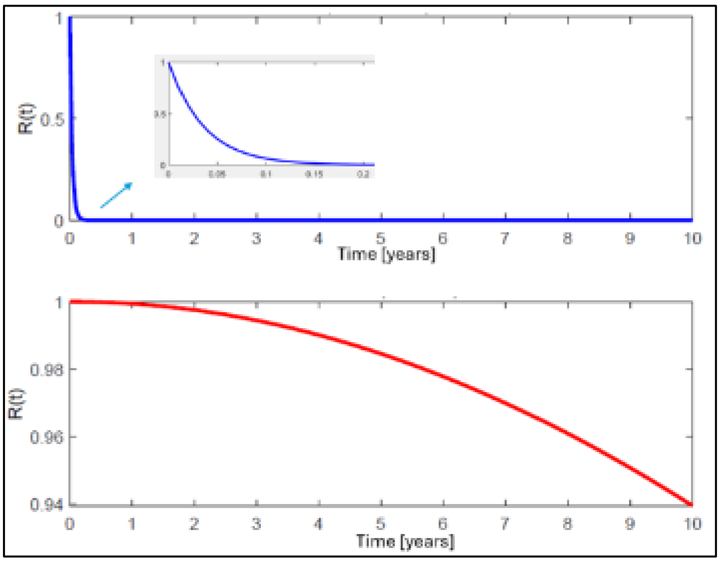

Figure 4 Results related to the reliability behavior considering the second scenario, characterized by a 20% failure rate and a repair time of 4.5 hours

Compared with the previous scenario (Figure 2), the redundant reliability curve exhibits a delayed degradation, reaching zero after approximately 0.2 years, whereas the reliability limit was reached around 0.1 years under the worst-case condition. This improvement demonstrates the positive influence of reducing the failure frequency and shortening the repair time on the overall network reliability. Furthermore, the results obtained from the exponential model, the Weibull model, and the redundancy-based approach confirm that a lower failure occurrence rate leads to an extension of the operational lifetime of the optical fiber system. However, the effectiveness of redundancy remains dependent on the intrinsic reliability of individual components and the adopted network architecture. These results underline the importance of combining adequate reliability modeling with optimized maintenance strategies to improve the availability of optical communication infrastructures.

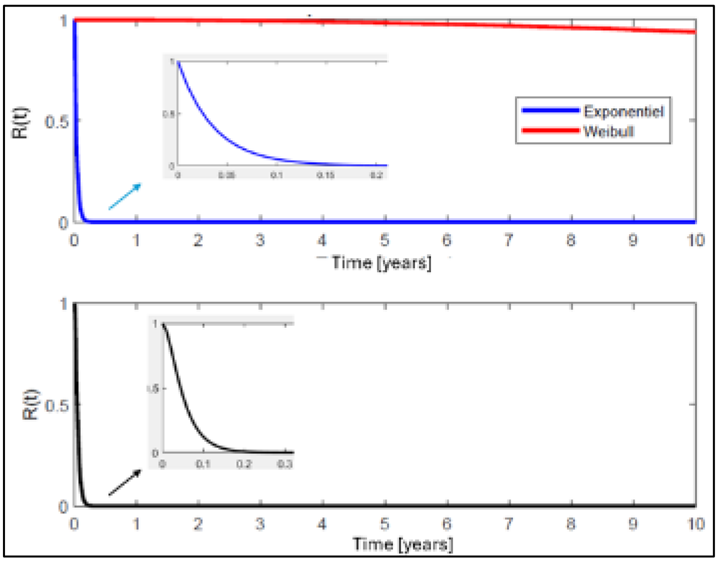

Figure 5 Reliability results in the presence of redundancy, considering a 20% failure rate and a mean repair time of 4.5 hours

4.7. Markov-Based Reliability Approach

4.7.1. Reliability Evolution Over 40 Years

Figure 6 presents the evolution of the optical fiber reliability R(t) over a 40-year period using the Markov model. The results show a progressive decrease in reliability over time, reflecting the cumulative effect of failure occurrences within the optical fiber network.

During the initial operating period, the reliability remains close to unity, indicating a low probability of failure and a highly available system. However, a significant degradation phase is observed between approximately 3 and 10 years, characterized by a faster reduction in reliability. The minimum reliability value reaches approximately 0.73 after 10 years, highlighting the impact of accumulated degradation mechanisms.

Beyond this period, the reliability curve tends toward a quasi-stationary behavior, with a slight recovery followed by stabilization around 0.74. This evolution can be attributed to the influence of maintenance and repair actions incorporated into the Markov model, which compensate for failure effects and prevent further degradation of the system.

These results demonstrate the balance between failure mechanisms and maintenance interventions, leading to a long-term steady-state reliability regime. Therefore, the Markov approach provides an effective framework for capturing the dynamic evolution of optical fiber reliability by considering both degradation and restoration processes.

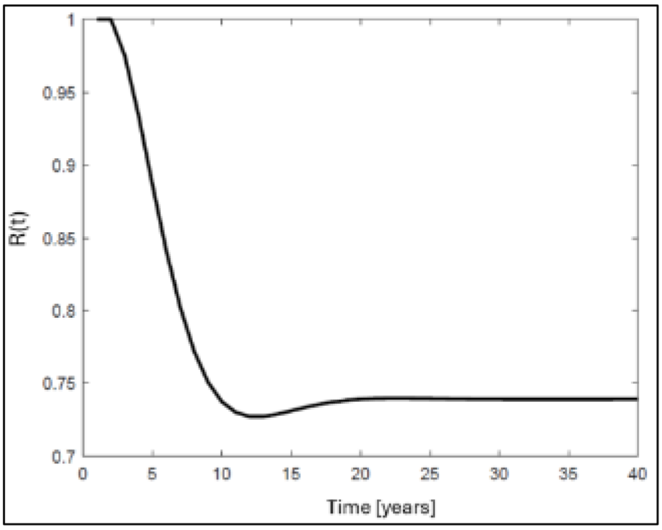

Figure 6 Results of the temporal evolution of the reliability function (R(t)), defined as the probability that the system remains operational at time (t), within a stochastic modeling framework incorporating failure and repair mechanisms

4.7.2. Five-State Markov Reliability Analysis

Figure 7 illustrates the dynamic evolution of the state probabilities of the optical fiber system modeled by a five-state Markov chain**:** perfect, attenuated, degraded, highly degraded, and failed states**.** The horizontal axis represents the operating time (years), while the vertical axis indicates the probability associated with each degradation state.

Initially, the probability of the perfect state is equal to unity, indicating an optimal initial operating condition. However, this probability rapidly decreases during the first years due to progressive degradation mechanisms. Simultaneously, the probabilities of intermediate states (attenuation, degraded, and highly degraded) increase gradually, reaching maximum values before approaching a stable regime.

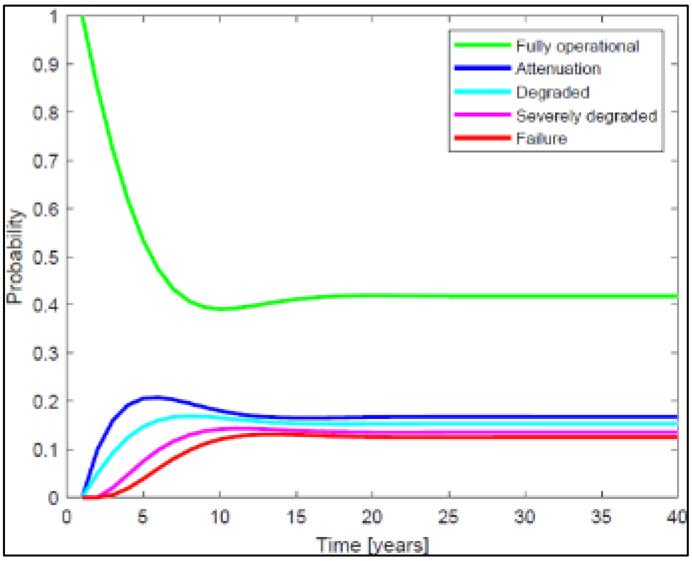

Figure 7 Results of the temporal evolution of the state occupation probabilities of an optical fiber system modeled using a homogeneous continuous-time Markov chain with five discrete states: perfect condition, attenuation, degraded condition, severely degraded condition, and failure. Each curve represents the probability $P_i(t)$ that the system is in state i at time t

The failure state, initially characterized by a zero probability, increases progressively over time, reflecting the accumulation of degradation effects and the increasing risk of permanent failure as the fiber ages. At long-term operation, all state probabilities converge toward quasi-constant values, indicating the establishment of a steady-state reliability condition.These results demonstrate the progressive transition of the optical fiber system from an initial healthy condition toward degraded and failed states, governed by the balance between degradation mechanisms and maintenance actions. The Markov approach provides a detailed representation of the fiber life cycle by incorporating intermediate degradation states, which cannot be accurately captured by conventional reliability models. This makes it a suitable tool for long-term reliability assessment and maintenance optimization of optical fiber networks.

5. Conclusion

This paper has presented a comprehensive reliability assessment framework for optical fiber communication systems, integrating a detailed analysis of physical degradation mechanisms, advanced modeling methodologies, and a practical network case study. The investigation underscores that the long-term performance and availability of optical infrastructures are governed by a complex interplay of mechanical, optical, environmental, thermal, and radiation-induced failure mechanisms, whose synergistic effects must be accurately characterized to ensure service continuity and operational stability.

The review of reliability modeling approaches has demonstrated that the selection of an appropriate analytical framework is critical for realistic performance prediction. While statistical models such as the exponential distribution offer simplicity for constant failure rate scenarios, the Weibull distribution provides a more representative description of the progressive aging and wear-out degradation inherent in optical fibers, as confirmed by the comparative analysis. Furthermore, Markov and semi-Markov stochastic models have proven to be powerful tools for capturing the dynamic evolution of degradation states and the influence of maintenance actions, offering a more nuanced representation of system life cycles than conventional analytical methods.

The practical reliability assessment of the Kongo Central optical fiber network served as a valuable case study, validating the theoretical models and highlighting the practical implications of the proposed framework. The analysis revealed that network reliability is highly sensitive to the annual failure rate and average repair time, with the Weibull model predicting a significantly longer service life compared to the conservative exponential model. The evaluation of redundancy strategies further demonstrated that their effectiveness is contingent upon the intrinsic reliability of individual components and the network architecture, emphasizing that redundancy alone is not a panacea. The Markov-based analysis provided additional insights into the long-term equilibrium between degradation and restoration processes, identifying a steady-state reliability regime that is crucial for maintenance planning.

The study establishes an integrated framework that bridges the gap between physical failure physics, theoretical reliability modeling, and network-level assessment. The main contributions of this work are threefold: (i) a systematic classification and analysis of the major failure mechanisms affecting optical fibers, (ii) a critical review and comparative evaluation of reliability modeling techniques, and (iii) a practical application of these models to a real-world regional network, providing actionable insights for reliability enhancement.

Future research should focus on the development of predictive maintenance strategies based on artificial intelligence and digital twin technologies, which could enable real-time health monitoring and remaining useful life estimation. Additionally, further work is needed to refine multifactorial environmental models and to investigate the long-term reliability of advanced fiber types, such as microstructured and hollow-core fibers, under diverse operational conditions. The integration of these approaches will be essential for building more resilient and intelligent optical communication infrastructures capable of meeting the ever-increasing demands of next-generation digital services.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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