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Reliability analysis of underground fiber optic infrastructure in Rural Areas: Case Study of the Matadi-Boma Section, Kongo Central Province, DRC

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Abstract

The reliability of fiber optic infrastructure is crucial for ensuring the continuity of digital services, particularly in rural areas of developing countries where environmental and operational challenges are significant. This study presents a reliability analysis of the underground fiber optic cable on the Matadi-Boma section of the national backbone in the Kongo Central province of the Democratic Republic of Congo. A mixed-method approach was employed, combining field observations, analysis of maintenance data from 2022 to 2025, and probabilistic modeling using both statistical (Exponential and Weibull) and stochastic (Markov chains) approaches. The field survey revealed that external factors specifically civil engineering works, erosion, and vandalism are the primary causes of cable cuts. Data analysis showed a direct correlation between the frequency of repairs (splicing) and increased optical losses, with a maximum splice loss of 3.94 dBm recorded in 2023. The developed Markov model with five degradation states effectively captured the progressive degradation of the optical fiber over time. The results confirm that a combined probabilistic approach provides a robust framework for assessing network reliability and optimizing maintenance strategies, thereby enhancing the resilience and durability of optical infrastructures in similar rural contexts.

Keywords: Reliability; Fiber Optics; Underground Infrastructure; Markov Chains; Weibull Distribution; Rural Areas; DRC; Matadi-Boma

1. Introduction

High-speed internet connectivity has become a critical infrastructure for human, economic, and social development worldwide [1]. For rural areas in developing countries, fiber optic cables are often the only viable solution for providing the high bandwidth required for modern digital services. However, the deployment of these infrastructures faces unique challenges related to environmental resilience, physical protection, and maintenance logistics [2], [3].

The Democratic Republic of Congo (DRC) has invested in a national fiber optic backbone to enhance its digital connectivity. A strategic segment of this backbone runs from the coastal city of Moanda to the capital, Kinshasa, traversing the rural areas of Kongo Central province. The underground cables in this region experience frequent technical difficulties, primarily attributed to rodent attacks and accidental damage from human activities [2]. The operator currently addresses these issues through a strategy of sectional repair, which involves cutting and splicing

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damaged cable sections. While this method restores service, it may negatively impact long-term cable performance by introducing additional optical losses and mechanical stress.

Given these challenges, understanding and predicting the reliability of this infrastructure is paramount. Reliability modeling, using both statistical and stochastic approaches, offers a quantitative framework for analyzing failure mechanisms, estimating remaining lifespan, and optimizing maintenance policies [4], [5]. This research aims to apply these probabilistic models to the Matadi-Boma section to evaluate its current state and propose strategies for improvement.

The primary research questions are:

- What are the main degradation mechanisms and failure causes affecting the underground fiber optic cables in the rural areas of Kongo Central?
- How can stochastic models (Markov chains) and statistical models (Weibull and Exponential laws) be applied to assess the reliability of this infrastructure?
- What maintenance and design strategies can be proposed to improve the network's durability and resilience?

The hypothesis is that the combined application of probabilistic models will provide an effective analysis of reliability and that failures are predominantly due to external factors rather than intrinsic aging.

2. Material and Methods

2.1. Study Area and Infrastructure Description

The study focuses on the underground fiber optic cable section between the cities of Matadi and Boma in the Kongo Central province, DRC. This section is part of the national backbone and is approximately **138 km** long. The infrastructure is a G.652D single-mode fiber cable with 24 cores, operating typically at 1310 nm and 1550 nm. Active network equipment includes Huawei OptiX OSN 9800 transmission platforms.

2.2. Data Collection and Field Survey

A field survey was conducted with the technical teams responsible for the network's operation and maintenance. Data were collected from the operator's historical records, covering a period from **2022 to 2025**. The collected data included:

- **Failure logs:** Dates, locations, and causes of cable cuts.
- **Maintenance reports:** Details of splicing operations, repair times, and optical power measurements (using OTDR and Power Meter).
- **Technical data:** Cable specifications and network topology.

Observations were also made on the ground regarding the environmental conditions and deployment practices.

2.3. Reliability Modeling Approach

Two complementary probabilistic approaches were used to model the reliability of the fiber optic link:

2.3.1. Statistical Modeling

- **Exponential Distribution:** This model assumes a constant failure rate (λ) over time and was used to model random failures that occur during the useful life of the component. The reliability function is $R(t) = e^{-\lambda t}$.
- **Weibull Distribution:** This more flexible model characterizes components with varying failure rates, representing aging and wear-out mechanisms. Its reliability function is $R(t) = e^{-(t/\eta)^{\beta}}$, where η is the scale parameter (characteristic life) and β is the shape parameter. $\beta > 1$ indicates an increasing failure rate, typical of wear-out.

Two scenarios were simulated to capture the variability in operational conditions:

- **Pessimistic Scenario:** High failure rate (35 per year) and long Mean Time To Repair (MTTR = 48 hours).
- **Optimistic Scenario:** Lower failure rate (20 per year) and short MTTR (4.5 hours, based on field observations).

2.3.2. Stochastic Modeling (Markov Chain)

A homogeneous continuous-time Markov chain model with five distinct states was developed to represent the progressive degradation of the optical fiber (Table 1). This model allows for the analysis of transitions between different levels of performance and failure.

Table 1 Markov Model States and Descriptions

State	Description
Perfect	The fiber is in optimal condition with no measurable degradation.
Attenuation	The fiber shows signs of increased attenuation but is still operational.
Degraded	The fiber exhibits significant degradation and is approaching a critical state.
Very Degraded	The fiber is in a near-failure state, with high probability of failure.
Failure	The fiber has failed, causing a complete interruption of service.

A transition matrix P was defined to represent the probabilities of moving between these states over a discrete time step (one year). The model calculates the probability of being in each state over time, and the overall system reliability is defined as the sum of probabilities of being in non-failure states (Perfect, Attenuation, and Degraded).

3. Results

3.1. Analysis of Operational Data

The analysis of the collected data (2022-2025) revealed several key trends (Table 2). The number of failures varied annually, with a peak in 2023. Field observations confirmed that the primary causes of these failures were external, including civil engineering works, erosion, and vandalism.

Table 2 Evolution of Key Performance Indicators (2022-2025)

Year	Failure Count	Max Section Loss (dB)	Average Splice Loss (dBm)	Max Splice Loss (dBm)
2022	3	31.573	0.133	1.326
2023	4	37.139	0.485	3.940
2024	4	32.221	0.782	1.457
2025	2	29.903	0.310	1.537

The significant increase in average and maximum splice losses in 2023 (Table 2) suggests that frequent repairs on the same cable sections can cumulatively degrade the quality of the optical link. This is likely due to the introduction of additional splice points and the potential for suboptimal splicing conditions.

3.2. Statistical Reliability Analysis

The reliability simulations using the Exponential and Weibull models revealed distinct behaviors.

- **Exponential Model:** This model showed a rapid decline in reliability, predicting near-zero survival probability within a short time frame for both the pessimistic and optimistic scenarios (Figure 1a). This indicates that the fiber optic system is highly vulnerable if its failure rate is considered constant at the observed levels.
- **Weibull Model:** This model showed a more gradual and realistic degradation over time, suggesting a significant survival probability even after 10 years (Figure 1b). The calculated Weibull failure rate increased over time, which is typical of wear-out mechanisms (Figure 1c). This model provided a more nuanced view of the network's performance, highlighting the progressive nature of degradation.

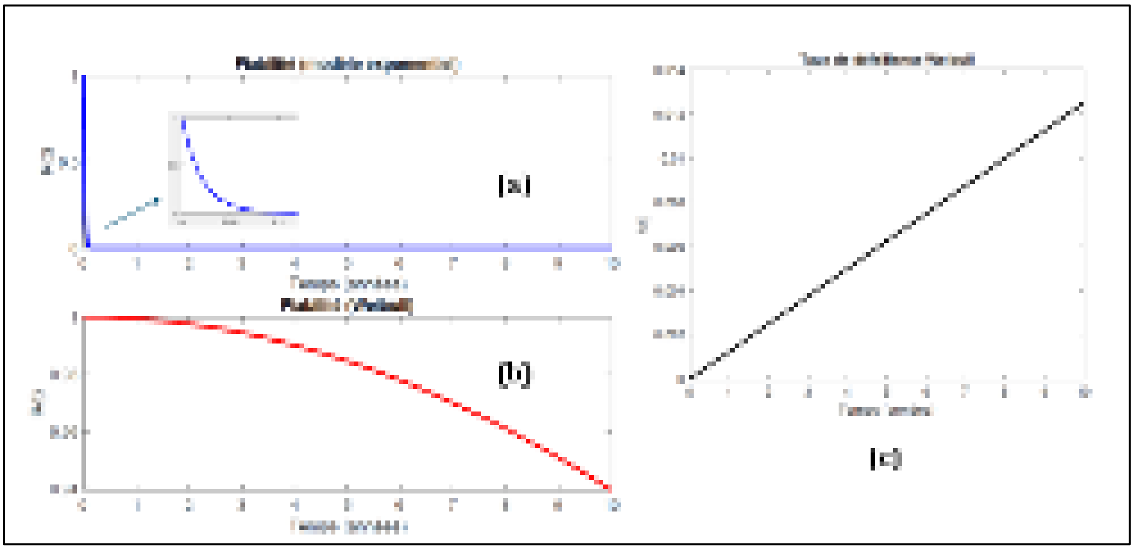

Figure 1 (a) Exponential Reliability (Pessimistic Scenario). (b) Weibull Reliability (Pessimistic Scenario). (c) Weibull Failure Rate over time

3.3. Stochastic Reliability Analysis (Markov Chain)

The Markov chain model provided a dynamic and comprehensive view of the system's evolution. The simulation over 40 years showed the probability of the system being in each state (Figure 2a).

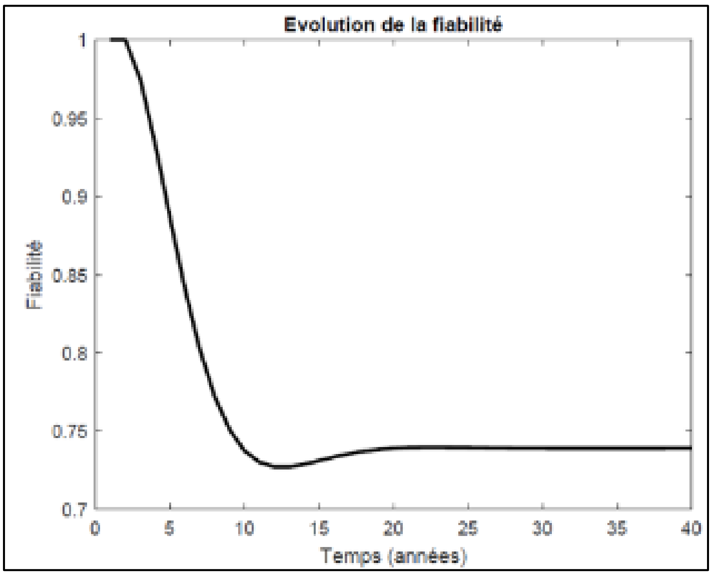

Figure 2a Markov Chain State Probabilities over 40 Years

Initially, the system is in a "Perfect" state (100%). Over time, the probability of being in this state decreases, while the probabilities of transitioning through "Attenuation," "Degraded," and "Very Degraded" states increase. The probability of being in a "Failure" state also gradually increases.

The overall reliability function, computed as the sum of the probabilities of the non-failure states (Perfect, Attenuation, Degraded), shows a decreasing trend but with a notable stabilization or "plateau" (Figure 2b). This suggests that after an initial period of degradation, the system reaches a quasi-stationary state where failures are balanced by maintenance and repair activities.

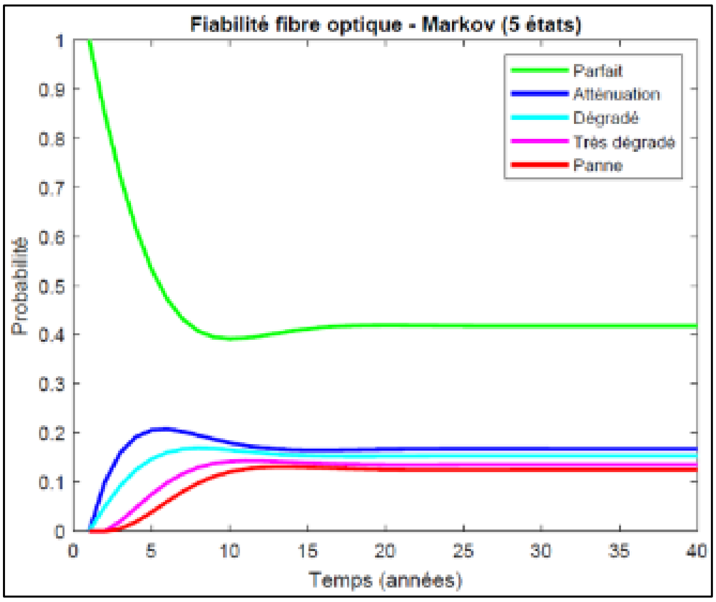

Figure 2b Overall System Reliability (Non-Failure States) over 40 Years

The reliability does not drop to zero, which is a more realistic representation of a repairable system like a fiber optic network.

4. Discussion

4.1. Validation of Field Hypotheses

The field diagnosis and data analysis confirm the main hypothesis of this study: the failures of the fiber optic cable in the Kongo Central province are predominantly due to **external factors**, such as civil engineering works, erosion, and vandalism, rather than intrinsic aging. This finding aligns with global observations on the primary causes of cable outages in rural areas [1], [2]. The high frequency of cuts (up to 35 per year) and the significant time required for repair (MTTR) are the main drivers of network unavailability.

4.2. Comparison of Modeling Approaches

The choice of reliability model significantly impacts the interpretation of the system's performance.

- **Exponential Model:** This model is analytically simple but provides a highly pessimistic and potentially unrealistic view of the network's reliability. Its assumption of a constant failure rate ignores the possibility of improvements from maintenance or the gradual wear-out of components. It serves as a good benchmark for a "worst-case" scenario.
- **Weibull Model:** This model is more flexible and realistic. It effectively captures the wear-out phase of the components, as indicated by an increasing failure rate over time. It is suitable for predicting failures due to aging and cumulative damage from repeated splicing.
- **Markov Model:** This is the most advanced and representative model for a repairable system like a fiber optic network. It provides a nuanced view of the system's life cycle by explicitly modeling transitions between different states of degradation (Table 1). The observed plateau in overall reliability (Figure 2b) is a key insight, suggesting that while the network is subject to wear and tear, a well-implemented maintenance strategy can prevent a total collapse of reliability and maintain a baseline level of service.

The results of the Markov model are consistent with the observed pattern of increasing splice losses and failures, followed by repair and restoration. The model demonstrates that the system can enter a quasi-stationary regime, where the probability of failure is balanced by the probability of repair, ensuring a certain level of long-term availability.

4.3. Implications for Maintenance and Design

The results provide clear direction for improving the network's reliability.

- **Maintenance Strategy:** The shift should be from reactive repair to **predictive maintenance**. The Markov model can be used to predict the time when the probability of being in a "Degraded" or "Very Degraded" state becomes unacceptably high, allowing for pre-emptive replacement of cable sections or splices before a failure occurs. Regular OTDR monitoring, as observed in the field, is crucial for identifying these degrading states.
- **Design and Protection:** Given the high impact of external factors, the design must prioritize physical protection. This includes burying cables at greater depths, using armored cables in high-risk zones, and implementing better cable route markers to avoid accidental damage during construction. While redundancy (a second fiber) can improve reliability, its cost-effectiveness needs to be evaluated against these preventative measures.

5. Conclusion

This study provides a comprehensive reliability analysis of the underground fiber optic infrastructure on the Matadi-Boma section, using a combination of field data and advanced probabilistic models. The key findings are:

- **Primary Failure Causes:** External factors, such as civil engineering works, erosion, and vandalism, are the dominant causes of network failures, confirming the study's initial hypothesis.
- **Model Application:** The Weibull and Markov models successfully captured the progressive degradation of the fiber due to aging and cumulative repair damage (splicing). The Markov model, in particular, offered a dynamic and realistic representation by modeling the network's state transitions.
- **Maintenance Impact:** There is a clear relationship between the frequency of repairs (splicing) and increased optical losses, which can accelerate the degradation of the fiber.

The proposed modeling framework provides a solid foundation for developing predictive maintenance strategies. By anticipating when the system is likely to transition into a highly degraded state, network operators can schedule proactive interventions, thereby reducing the number of unplanned outages, lowering operating costs, and improving service availability.

Future work should focus on integrating this reliability model with a techno-economic analysis to optimize the balance between maintenance costs and the value of service availability. Furthermore, incorporating data from other sections of the national backbone would allow for a more robust and generalized reliability model for the entire DRC network.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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