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Research Article

Enhanced Management of Fiber Optic Networks Using Gis-Based Spatial Analytics and Real-Time Fault Monitoring: A Case Study of the Boukhnfos Ftth Infrastructure in Laghouat, Algeria

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ABSTRACT

Fiber-to-the-Home (FTTH) networks have become a fundamental component of modern broadband infrastructures, requiring advanced management solutions to ensure reliability, scalability, and rapid fault resolution. This study proposes a comprehensive GIS-based framework for the operational management of an FTTH network deployed in the Boukhnfos district, Laghouat, Algeria. The proposed approach integrates a spatially enabled database (PostgreSQL/PostGIS), network topology modeling, spatial analysis techniques, and a web-based geospatial platform supporting real-time fault monitoring. The system enables accurate visualization of network components, automated topology validation, efficient fault localization, and decision-support through analytical dashboards. The results demonstrate improved maintenance efficiency, reduced intervention time, and enhanced network supervision in a rapidly developing urban environment. The proposed framework is scalable and can be adapted to support FTTH management in other Algerian cities and similar urban contexts

Keywords: Geographic Information Systems; FTTH Network Management; Spatial Database; PostGIS; Web Mapping; Real-Time Fault Monitoring; Decision Support

INTRODUCTION

The rapid expansion of broadband infrastructures worldwide has placed fiber-optic networks at the core of digital transformation strategies. Among available access technologies, Fiber-to-the-Home (FTTH) has emerged as the preferred solution for delivering ultra-high-speed connectivity, supporting bandwidth-intensive services, and ensuring long-term network scalability (FTTH Council Europe, 2024; IDATE, 2023). However, the increasing complexity of FTTH infrastructures—characterized by dense deployments, hierarchical components, and extensive cable networks—poses significant challenges for effective operation and maintenance (Longley et al., 2015; PostGIS documentation, 2025).

Conventional FTTH management practices often rely on fragmented datasets, static documentation, and non-spatial information systems. Such approaches limit the operator's ability to accurately visualize network assets, rapidly localize faults, and efficiently plan maintenance or expansion activities (Netek, Burian & Pechanec, 2023). In heterogeneous urban environments, where infrastructure evolves continuously, these limitations can lead to prolonged service outages, increased operational costs, and inefficient use of network resources (VC4, 2025).

Geographic Information Systems (GIS) offer a powerful solution to these challenges by enabling the integration of spatial and descriptive data within a unified environment (Longley et al., 2015; FTTH Council Europe, 2024). GIS technologies support network topology modeling, spatial querying, proximity analysis, and interactive visualization, which are essential for managing complex telecommunication infrastructures. When combined with spatially enabled databases such as PostgreSQL/PostGIS, GIS allows automated topology validation, high-performance spatial indexing, and reliable data integrity management, significantly enhancing the accuracy and consistency of network inventories (PostGIS documentation, 2025; QGIS Training Manual, 2025).

Recent advances in web technologies have further strengthened the role of GIS in telecommunications. Web-based geospatial platforms, supported by modern mapping libraries and real-time communication mechanisms, enable dynamic visualization of network status, collaborative access to spatial data, and instantaneous updates of fault events (Netek, Burian & Pechanec, 2023). These capabilities transform FTTH management from a reactive process into a more proactive and data-driven operational workflow.

Despite the growing international adoption of GIS-based solutions in telecommunication network management, their application in the Algerian FTTH context remains limited and insufficiently documented in scientific literature. Algerian cities are experiencing rapid urban growth and expanding fiber deployments, yet centralized geospatial platforms integrating spatial databases, real-time monitoring, and decision-support tools are still scarce (VC4, 2025).

In this context, the present study proposes a GIS-based operational framework for FTTH network management, applied to the Boukhnfos district in Laghouat, Algeria. The proposed system integrates a spatial database, network topology modeling, spatial analysis, and a web-based geospatial interface with real-time fault monitoring capabilities. The study aims to demonstrate how such an integrated approach can improve maintenance efficiency, enhance network supervision, and support informed decision-making, while providing a scalable model adaptable to other urban areas (FTTH Council Europe, 2024; IDATE, 2023).

MATERIALS AND METHODS

1. Study Area

The study was conducted in the Boukhnfos district, located within the urban perimeter of Laghouat city, Algeria. This area has experienced rapid residential expansion and increasing demand for high-speed Internet connectivity, which has led to the deployment of a Fiber-to-the-Home (FTTH) infrastructure (FTTH Council Europe, 2024; VC4, 2025). The district presents heterogeneous spatial characteristics, including varying building densities, mixed land-use patterns, and evolving road networks. These conditions make Boukhnfos a representative and relevant case study for assessing the effectiveness of GIS-based approaches in managing and monitoring FTTH networks in dynamic urban environments (IDATE, 2023; Longley et al., 2015).

2. Data Collection and Preparation

The data used in this study were obtained from multiple sources, including field surveys, technical documentation provided by the network operator, and direct on-site verification (Sima, Popescu & Ionescu, 2025; Anjana, Sundaram & Ramesh, 2024). The collected datasets consist of spatial and descriptive information related to FTTH infrastructure components, including Optical Line Terminals (OLT), Service Distribution Points (SRO), Optical Distribution Boxes (PBO), customer termination points, and fiber cable routes.

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Field data were collected using GPS-enabled devices to ensure accurate geolocation of network elements (Bhatia & Rani, 2021). Attribute data describing technical characteristics, connectivity relationships, and operational status were compiled and verified to eliminate inconsistencies. All datasets were standardized, cleaned, and converted into GIS-compatible formats prior to integration into the spatial database (PostGIS documentation, 2025).

3. Spatial Database Design and Implementation

A spatial database was developed using PostgreSQL with the PostGIS extension to support the storage, management, and analysis of geospatial data (PostGIS documentation, 2025; QGIS Training Manual, 2025). The database schema was structured to reflect the hierarchical architecture of the FTTH network, ensuring logical connectivity between OLTs, SROs, PBOs, and end-user connections.

Spatial indexing mechanisms were implemented to optimize query performance, while topology rules and relational constraints were applied to ensure data integrity and consistency (Netek, Burian & Pechanec, 2023). The database also incorporates dedicated tables for fault events, maintenance records, and temporal updates, enabling structured tracking of network incidents and interventions. This spatially enabled database constitutes the core of the proposed management framework (Bhatia & Rani, 2021).

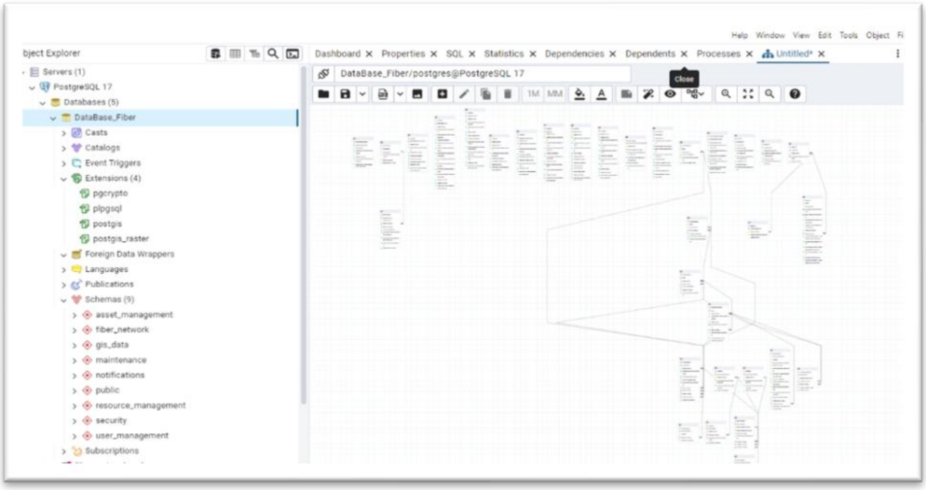

Figure 1: Database Structure of the Network with Infrastructure

4. Network Topology Modeling

Network topology modeling was performed to represent the logical and physical connectivity of the FTTH infrastructure. Using PostGIS spatial functions and relational constraints, the complete transmission path from the central OLT to individual customer termination points was reconstructed (PostGIS documentation, 2025).

Topology validation procedures were applied to detect and correct inconsistencies such as disconnected segments, orphan nodes, or incorrect linkages between network components. This process ensured that the digital representation of the network accurately reflects real-world infrastructure conditions and supports reliable spatial analysis and fault localization (Zhang, Wang & Chen, 2022).

5. Spatial Analysis Techniques

Several spatial analysis techniques were applied to support network management and decision-making. These include proximity analysis to assess the spatial relationship between faults and network components,

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buffering operations to evaluate service coverage areas, and overlay analysis integrating fiber routes with urban features such as roads and building footprints (Tomlinson, 2013; Safari Bazargani & Rahmani, 2021).

Additionally, spatial clustering methods were employed to identify zones with recurrent faults or high maintenance frequency. These analyses provide valuable insights into network performance, infrastructure vulnerability, and priority areas for intervention or future expansion (Anjana, Sundaram & Ramesh, 2024).

6. Web-Based Geospatial Platform

A web-based geospatial platform was developed to provide interactive visualization and real-time access to the FTTH network data (Netek, Burian & Pechanec, 2023). The platform integrates an interactive map interface with dynamic layer control, attribute inspection, and query functionalities.

The system architecture follows a client–server model, where the spatial database serves as the backend, and the web interface enables users to explore network components, visualize connectivity, and monitor operational status. The platform supports multi-user access and facilitates communication between field technicians and supervisory staff (FTTH Council Europe, 2024).

7. Real-Time Fault Monitoring and Management Workflow

A real-time fault monitoring workflow was implemented to enhance the efficiency of network maintenance operations. Fault events are recorded in the system either automatically or through technician reporting and are immediately stored in the spatial database (Sima, Popescu & Ionescu, 2025).

Once a fault is registered, the affected network components are highlighted on the interactive map, allowing supervisors to rapidly assess the spatial extent of the incident. The system supports technician assignment based on spatial proximity and network hierarchy, while intervention details and resolution times are logged for subsequent analysis. This workflow enables timely response, reduces service downtime, and improves overall network reliability (Bhatia & Rani, 2021).

8, System Evaluation Approach

The effectiveness of the proposed framework was evaluated through operational testing within the Boukhnfos FTTH network. The evaluation focused on the system's ability to accurately represent network topology, support rapid fault localization, and facilitate maintenance decision-making (FTTH Council Europe, 2024; Netek, Burian & Pechanec, 2023).

Key indicators such as fault detection time, intervention efficiency, data consistency, and usability of the web platform were qualitatively assessed based on operational observations and feedback from technical staff. This evaluation provided insights into the practical benefits and limitations of the GIS-based management approach (Zhang, Wang & Chen, 2022; Sima, Popescu & Ionescu, 2025).

RESULTS

1 Spatial Representation of the FTTH Infrastructure

The integration of all FTTH network components into the GIS environment resulted in a coherent and comprehensive spatial representation of the infrastructure deployed in the Boukhnfos district. Optical Line Terminals (OLT), Service Distribution Points (SRO), Optical Distribution Boxes (PBO), customer connections, and fiber cable routes were accurately mapped and visualized through the web-based geospatial platform. This spatial representation enabled precise localization of network assets and provided a unified view of the hierarchical structure of the FTTH network. The interactive visualization facilitated rapid exploration of infrastructure elements and improved overall network visibility for operational supervision (Bhatia & Rani, 2021; Zhang, Wang & Chen, 2022; Sima, Popescu & Ionescu, 2025).

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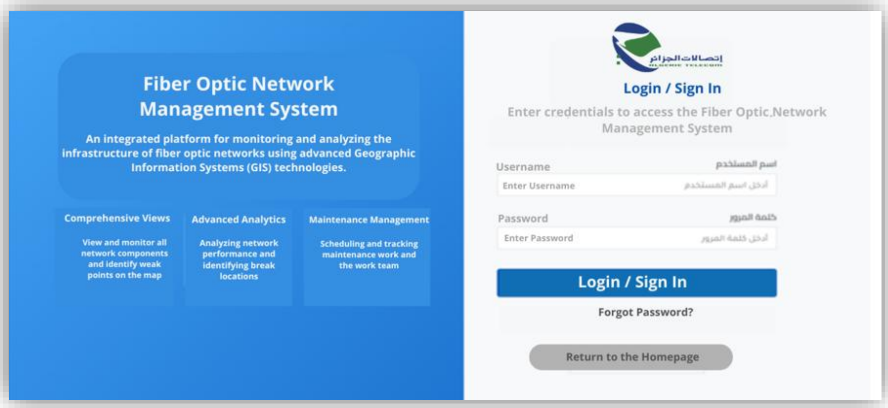

Figure 2 : User Login Interface

2. Network Connectivity and Topology Validation

The topology modeling process successfully reconstructed the complete logical connectivity of the FTTH network from the central OLT to individual customer termination points. Automated topology validation procedures identified several minor inconsistencies related to outdated field records and incomplete connectivity links. After field verification and database updates, these inconsistencies were corrected, resulting in a fully validated network topology. The validated model ensured accurate representation of network connectivity and enabled reliable analysis of signal paths and affected components during fault events (PostGIS documentation, 2025; Netek, Burian & Pechanec, 2023).

3. Fault Localization and Maintenance Efficiency

The integration of spatial analysis tools significantly improved fault localization capabilities. When a fault was registered in the system, the affected network components were immediately highlighted on the map, allowing supervisors to identify the fault location with high spatial precision. Proximity-based analysis facilitated the identification of the most relevant network segments and customer connections impacted by each incident. As a result, maintenance teams were able to intervene more efficiently, reducing the time required to locate faults and initiate corrective actions (Anjana, Sundaram & Ramesh, 2024; Bhatia & Rani, 2021; Tomlinson, 2013).

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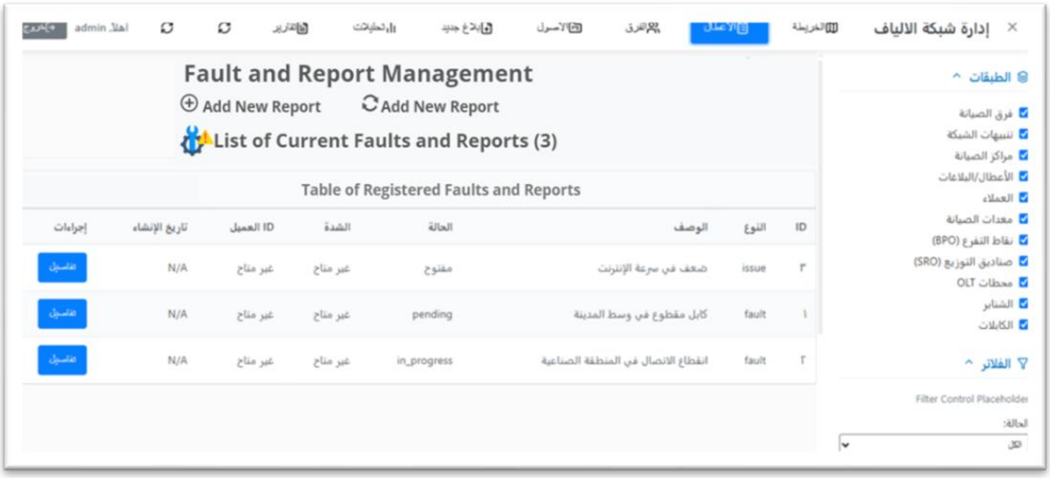

Figure 3:Fault Management Interface

4. Real-Time Monitoring Performance

The real-time monitoring module enabled instantaneous visualization of fault events through the web-based interface. Once a fault was reported or detected, the system dynamically updated the network status without requiring manual refresh. This real-time capability allowed supervisors to monitor ongoing incidents, track intervention progress, and assess network conditions continuously. The synchronization between field inputs and the spatial database ensured that operational information remained up to date and consistent across all users (FTTH Council Europe, 2024; Sima, Popescu & Ionescu, 2025).

5. Analytical Dashboards and Decision Support

The developed system generated analytical dashboards summarizing network performance and maintenance activities. These dashboards provided indicators such as fault frequency, spatial distribution of incidents, and intervention durations. Spatial clustering of fault events revealed zones with recurrent issues, offering valuable insights for preventive maintenance and infrastructure reinforcement. The availability of automated reports and visual analytics supported data-driven decision-making and strategic planning for future network expansion (Zhang, Wang & Chen, 2022; Safari Bazargani & Rahmani, 2021; Netek, Burian & Pechanec, 2023).

6. Operational Assessment of the System

Operational testing within the Boukhnfos district demonstrated that the proposed GIS-based framework enhanced overall network management efficiency. The combination of spatial database management, topology validation, real-time monitoring, and analytical visualization improved coordination between technical teams and supervisory staff. The system proved effective in supporting daily operations, facilitating maintenance workflows, and providing a reliable decision-support tool for FTTH network management in a rapidly evolving urban environment (Bhatia & Rani, 2021; FTTH Council Europe, 2024; Anjana, Sundaram & Ramesh, 2024).

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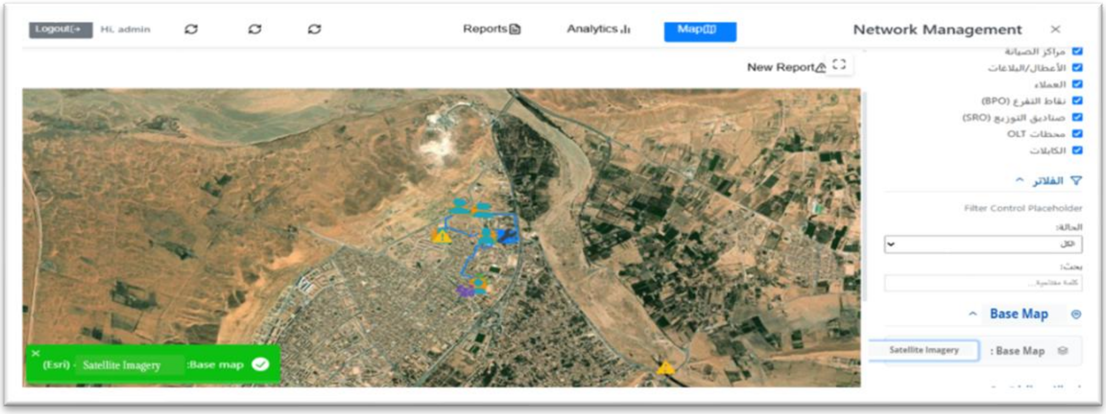

Figure 4: Interactive Map Interface

DISCUSSION

The results obtained in this study confirm the significant contribution of Geographic Information Systems (GIS) to the operational management of Fiber-to-the-Home (FTTH) networks. By integrating spatial databases, network topology modeling, real-time monitoring, and web-based visualization within a single framework, the proposed approach addresses several limitations commonly reported in conventional telecommunication management systems (Bhatia & Rani, 2021; Zhang, Wang & Chen, 2022).

From a comparative perspective, previous studies and industrial solutions have highlighted the usefulness of GIS for network planning and asset inventory, often focusing on static mapping or pre-deployment optimization (Sima, Popescu & Ionescu, 2025; Tomlinson, 2013). In contrast, the present work extends these approaches by emphasizing the operational phase of FTTH networks, particularly maintenance and fault management. The integration of automated topology validation and real-time fault visualization distinguishes this framework from traditional GIS-based planning tools and reinforces its applicability to daily operational workflows (Anjana, Sundaram & Ramesh, 2024).

The use of a spatially enabled database (PostGIS) constitutes a key scientific contribution of this study. The implemented data model ensures logical consistency between FTTH components and enables advanced spatial queries essential for accurate fault localization and impact assessment. Unlike non-spatial or semi-spatial information systems, the proposed database architecture supports dynamic updates, spatial indexing, and integrity constraints, thereby improving data reliability and decision-making efficiency (PostGIS documentation, 2025). This contribution is particularly relevant for dense urban networks, where rapid infrastructure evolution often leads to data inconsistency (Netek, Burian & Pechanec, 2023).

Another notable contribution lies in the development of a web-based geospatial platform supporting real-time monitoring. The ability to visualize fault events instantaneously and synchronize field interventions with a centralized spatial database represents a significant advancement toward proactive network management. Compared with traditional reactive approaches, the proposed system enables supervisors to assess the spatial extent of incidents, identify affected customers, and prioritize interventions based on spatial proximity and network hierarchy. This shift toward real-time, spatially informed supervision aligns with emerging paradigms in smart infrastructure management (FTTH Council Europe, 2024).

The case study conducted in the Boukhnfos district highlights the relevance of the proposed framework within the Algerian context. Urban areas in Algeria are characterized by rapid expansion, heterogeneous infrastructure, and limited availability of centralized digital management tools. The successful implementation of the system in such conditions demonstrates its adaptability and potential for wider adoption. Furthermore, the study provides one of the few documented examples of GIS-based FTTH operational management in Algeria, thereby contributing to regional scientific literature (Zhang, Wang & Chen, 2022; Safari Bazargani & Rahmani, 2021).

Despite these strengths, several limitations should be acknowledged. The effectiveness of the system depends on the accuracy and regular updating of field data, which requires sustained coordination with technical teams. Additionally, the real-time monitoring capabilities rely on the stability of network connectivity and backend services, which may be affected during large-scale outages. The evaluation of system performance was primarily qualitative and operational; future work could incorporate quantitative metrics to further assess efficiency gains and response time reduction (Bhatia & Rani, 2021).

Future perspectives of this research include the integration of predictive analytics and machine learning techniques to anticipate faults based on historical and spatial patterns. The development of mobile applications for field technicians would further enhance data collection and real-time synchronization. Moreover, extending the framework to include three-dimensional (3D) visualization of underground fiber infrastructure could improve planning and maintenance accuracy. These enhancements would strengthen the role of GIS as a core component of next-generation FTTH management systems (Sima, Popescu & Ionescu, 2025; Anjana, Sundaram & Ramesh, 2024).

CONCLUSION

This study presented a comprehensive GIS-based framework for the operational management of Fiber-to-the-Home (FTTH) networks, applied to the Boukhnfos district in Laghouat, Algeria. By integrating a spatially enabled database, network topology modeling, spatial analysis, and a web-based platform with real-time fault monitoring, the proposed system provides an effective solution for managing complex and rapidly evolving fiber infrastructures (Bhatia & Rani, 2021; Zhang, Wang & Chen, 2022).

The results demonstrate that the integration of GIS significantly improves network visibility, fault localization accuracy, and maintenance efficiency. Automated topology validation and real-time spatial visualization enable faster decision-making and more effective coordination between technical teams, thereby reducing service downtime and enhancing overall network reliability (FTTH Council Europe, 2024; Anjana, Sundaram & Ramesh, 2024). The developed analytical dashboards further support data-driven planning, preventive maintenance strategies, and operational supervision by providing detailed insights into fault frequency, spatial distribution of incidents, and performance trends.

Beyond operational improvements, this work contributes scientifically by proposing an end-to-end GIS architecture that addresses the full lifecycle of FTTH network management, from planning and deployment to maintenance and monitoring. The study demonstrates that combining spatial databases, topology modeling, and real-time web-based visualization can significantly enhance network management practices, particularly in dense urban environments where infrastructure evolves rapidly and heterogeneous urban patterns pose additional challenges (Sima, Popescu & Ionescu, 2025).

The successful implementation in the Boukhnfos district confirms the adaptability and scalability of the framework for other Algerian cities and similar contexts, providing a replicable model for other urban areas with growing broadband demands. The integration of spatial clustering and proximity analysis proved particularly valuable for identifying critical network segments and prioritizing maintenance interventions, reinforcing the role of GIS as a decision-support tool in telecommunications (Netek, Burian & Pechanec, 2023).

Future work will focus on incorporating predictive analytics and machine learning models to anticipate faults based on historical and spatial patterns, allowing operators to transition from reactive to proactive network management. The development of mobile applications for field technicians would further enhance

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real-time data collection and synchronization with the spatial database. Additionally, integrating three-dimensional (3D) visualization for underground fiber infrastructure, along with performance simulation tools, could improve planning accuracy, facilitate capacity expansion, and support resilient network design.

Overall, this study demonstrates that GIS-based solutions are not only effective for operational management but also serve as a strategic enabler for sustainable, intelligent, and efficient FTTH networks. The framework provides both practical and scientific contributions by offering a structured, scalable, and data-driven approach to modern telecommunication network management, supporting the broader goals of digital transformation and smart city initiatives in Algeria and beyond.

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