

Predictive Maintenance and Reliability Modeling of Rural Broadband Networks: A Condition-Based Study of BharatNet Infrastructure

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ABSTRACT

This study explores the operational status and reliability of rural broadband infrastructure in 113 Gram Panchayats (GPs) in the Puducherry district, focusing on critical assets such as Optical Network Terminals (ONT), Central Control Units (CCU), battery systems, and solar panels, using a condition-based performance evaluation. Results from data analysis in SPSS show that 87.6% of GPs are operational ("UP"), but technical issues, including high fault rates in earthing and solar systems, are still prevalent, highlighting the need for predictive maintenance and real-time monitoring to ensure uninterrupted rural connectivity in support of India's digital empowerment objectives.

INTRODUCTION

The digital revolution has changed the socio-economic fabric of modern nations, but a key challenge remains in the disparity between urban and rural connectivity (Larsson, 2023). The BharatNet project is at the core of the Digital India vision and aims to transform 250,000 Gram Panchayats (GPs) into digitally enabled Gram Panchayats. In the Union Territory of Puducherry, this infrastructure is not just a technical installation but a public utility, with its backbone (ONT, CCU, solar panels and battery backups) providing the main access point for rural citizens to access e-governance, tele-education, and digital commerce. The research presented here explores a predictive and condition-based analysis of these assets to ensure that the promise of connectivity becomes realized in the delivery of high-quality service (Hagen & Andersen, 2024).

Theoretical Framework

To evaluate the efficacy and sustainability of rural broadband infrastructure, this research draws upon four primary academic lenses:

Technology Acceptance Model (TAM): While installation is a technical task, the success of BharatNet will depend on user adoption; TAM posits that the key factors in whether or not rural communities will integrate these digital tools into their daily lives are Perceived Usefulness (reliable, high-speed access) and Perceived Ease of Use (seamless integration via solar backups) (Davis, 1989)

Diffusion of Innovation (DOI) Theory: DOI theory focuses on how new technological standards, such as solar-powered broadband nodes, diffuse across administrative blocks (Rogers, 2003); it notes that the Rate of Adoption in Puducherry is often mediated by local technical literacy and availability of immediate maintenance support (Pfeffer & Salancik, 1978; Larsson, 2023).

Resource Dependence Theory (RDT): This framework focuses on how local Gram Panchayats are dependent on external resources (stable grid power and centralized data networks); the study employs RDT to advocate for decentralized energy (solar) as a means to mitigate dependence. (Pfeffer & Salancik, 1978; Larsson, 2023)

Statement of the Problem

Although Puducherry has aggressively rolled out high-speed fiber, there is a big difference between the presence of infrastructure and the availability of service. Rural networks suffer from downtime due to equipment degradation, environmental stressors, and delayed maintenance response; current operational models are often reactive and begin repairs only after a total service outage is reported, which results in long periods of blackout and loss of public confidence in digital governance (**Larsson, 2023**). The urgent question becomes: How can we analyze the current condition of the hardware to create a predictive maintenance strategy that prevents failures?

Industry and Regional Context

Evolution of Rural Digital Infrastructure in India

The Indian telecommunications sector has transitioned to "last-mile connectivity." The BharatNet project under Bharat Broadband Network Limited (BBNL) is the largest rural broadband project in the world. In Puducherry, this has been implemented through a complex mix of public sector undertakings such as BSNL and private partners such as Polycab and Xentric Integrated Solutions. This ecosystem is not a silo and feeds into other "related industries"(Larsson, 2023):

1. Telecommunications: Fiber backbone for 4G/5G rollout
2. Renewable Energy: Driving demand for localized solar-storage solutions
3. Data Analytics: Utilizing performance data to optimize network traffic and maintenance schedules.

Competitive Landscape and Stakeholder Analysis

What started as a mandate to connect rural India has become a competitive space where public mandates clash with private efficiency as private giants like Reliance Jio, Bharti Airtel, and Vodafone Idea compete to deliver last-mile services through government contracts(Larsson, 2023).

The supply chain for hardware is backed by industrial leaders(Hagen & Andersen, 2024):

•**Sterlite Technologies (STL):** a global optical fiber and integrated digital network solution provider•

KEI Industries: offers heavy-duty cabling to suit varying terrains.

system integrators: firms like Xentric, play a critical role in connecting the hardware procurement to field-level operationality.

This competition requires the infrastructure to be at a high level of performance, making condition-based analysis a necessity rather than an option for those who want to keep their contractual and operational edge.

REVIEW OF LITERATURE

A review of the existing literature reveals that a shift from reactive to proactive maintenance strategies has been observed in the large-scale rural infrastructure projects. Some key thematic areas from the literature are:

Need for Data-Driven Models: Traditional maintenance in many photovoltaic (PV) and telecom systems is still corrective (reactive) or schedule-driven, which often leads to significant downtime and lower-than-expected system performance; the authors (Larsson, 2023) &(Hagen & Andersen, 2024) stress the need for a transition to predictive and prognostic maintenance using data-driven methods for identifying potential failures before service disruption occurs; and research indicates that economic models can be used to balance maintenance costs with component reliability and system performance.

Sustainable Energy and Battery Management

Degradation due to high state-of-charge (SOC) corrosion is a dominant aging mechanism in lead-acid batteries in solar home systems, and researchers (Wei, 2023, Perriment et al., 2023) have proposed intelligent battery management systems (BMS) to extend battery life by up to 25% through adaptive charging protocols based on real-time field data. • A recent review of 186 studies in the PV sector demonstrates the need for designing maintenance strategies around certain performance and reliability indicators.

Optical Network Optimization

There is a trade-off between attenuation thresholds and operational costs: Research on PON suggests that too low a threshold causes unnecessary technician dispatches, and too high a threshold puts service quality at risk, so data-driven policies are recommended to balance service-level agreements (SLAs) with maintenance expenditures. In short-reach optical systems and photovoltaic (PV) systems more and more ML models are being employed for anomaly detection to increase the accuracy and interpretability of fault diagnosis (Shao et al., 2024)

Emerging Technologies in Infrastructure Monitoring

Machine Learning (ML) Applications: ML techniques are being widely adopted for anomaly detection in photovoltaic (PV) systems and short-reach optical networks, enhancing the precision, reliability, and interpretability of fault diagnosis (Shao et al., 2024).

• **Federated Learning:** For large, geographically distributed deployments such as BharatNet, federated learning enables collaborative, data-driven monitoring while avoiding centralized storage of raw data, thus safeguarding data privacy and minimizing communication and bandwidth overhead (Larsson, 2023).

Research Gaps Identified

Despite extensive research in individual domains, several gaps remain:

Lack of Integrated Site Diagnosis: Most studies focused and considered solar systems and telecom hardware as separate entities, without taking them as combined frameworks that assess solar, battery, and networking equipment (ONT/CCU) collectively (Hagen & Andersen, 2024)..

Limited Rural Field Data: While hypothetical models exist, there is a insufficiency of empirical studies focusing on the real-time reliability of telecom field infrastructure specifically in rural or semi-urban geographies (Larsson, 2023).

Visualization for Field Support: There is a significant lack of user-friendly, concurrent decision-support dashboards specifically designed for field technicians to quickly identify multi-component faults at remote sites. (Hagen & Andersen, 2024).

RESEARCH METHODOLOGY

The research methodology for this study is designed to assess the operational consistency of rural broadband infrastructure using a data-driven, analytical approach. It utilizes a blend of descriptive, diagnostic, and predictive methods to assess the performance of critical hardware assets.

Research Design

The study employs a **descriptive and analytical research design**.

Descriptive Analysis: Used to analyze the current availability and health status of equipment across 113 Gram Panchayats (GPs).

Diagnostic Analysis: Focused on identifying the origin reason of network downtime, such as equipment failure clusters or power supply gaps.

Predictive Analysis: Leveraged to institute a framework for anticipating future maintenance needs based on existing equipment conditions.

Data Collection and Sources

The study exclusively depends on **secondary data** collected from the internal field operations and maintenance records of Xentric Integrated Solutions Pvt. Ltd..

Primary Source: Regular site inspection reports, infrastructure logs, and maintenance records from the BharatNet rural broadband network.

Parameters Tracked: Data includes technical conditions of Optical Network Terminals (ONT), Central Control Units (CCU), battery backups, solar panels, earthing systems, building stability, and Electricity Board (EB) power availability.

Verification: Data was initially gathered by field engineers and later verified against the company's Network Operations Center (NOC) support logs.

Sampling Design

The research uses a structured sampling plan to ensure representation of both geographic and technical factors across the Puducherry district.

- **Sampling Method:** A **non-probability purposive sampling** method was adopted. This method was chosen because the study required existing technical inspection data rather than subjective opinions from public users.
- **Sampling Unit:** Each individual Gram Panchayat (GP) network site served as the primary unit of observation.
- **Sample Size:** The total sample consists of **113 Gram Panchayat network sites** across three administrative blocks: Ariyankuppam, Villianur, and Karaikal.
- **Sampling Frame:** The frame comprises 113 commissioned and active sites documented in the company's asset maintenance database

Data Preprocessing and Analysis Plan

To make sure data accuracy, the dataset underwent thorough cleaning and preparation before analysis:

1. **Cleaning:** elimination of duplicate entries, correction of location names, and standardization of categorical statuses (e.g., "Healthy/Faulty").
2. **Tools:** Data cleaning and initial analysis were performed using **Microsoft Excel** and **Google Sheets**, while complex statistical modeling was conducted in **SPSS**.
3. **Statistical Techniques:** The study utilized frequency distribution, cross-tabulation, correlation analysis (to identify interdependencies between ONT and CCU systems), and **logistic regression** to predict GP operational status based on equipment health.

Data Analysis and Interpretations

This section presents the data analysis and interpretations derived from the study of 113 Gram Panchayats (GPs) in Puducherry. The analysis focuses on the operational status and health of core hardware assets, including Optical Network Terminals (ONT), Central Control Units (CCU), battery systems, and solar panels

General Operational Status

The study categorized the operational status of GPs as "UP" (functional) or "DOWN" (non-functional) based on their connectivity and equipment health.

Table 1. Categorization of operational status

GP Name	ONT Status	CCU Status	Battery Status	Solar Panel Status	Building Condition
GP 101	Healthy	Healthy	Missing	Healthy	Good
GP 102	Healthy	Faulty	Healthy	Missing	Needs Repair

Table 2. Descriptive statistics

Category	Component	Available (Frequency)	Available (%)	Faulty (Frequency)	Faulty (%)
Networking	ONT	98	86.73%	2	2.04%
Networking	CCU	91	80.53%	1	1.10%
Power	Battery	78	69.03%	4	5.13%
Power	Solar Panel	67	59.29%	6	8.96%

A majority (**87.61%**) of the Gram Panchayats are operational. However, the **12.39%** designated as "DOWN" represent significant service gaps, primarily due to equipment failure or a total lack of critical hardware

Equipment Health and Availability

Based on table 2 the Networking Hardware such as ONTs and CCUs show the highest availability and healthiest operational status, representing a healthy primary network infrastructure. In case of Power Backup Gaps: There is significant drop-off in the availability of batteries (69%) and solar panels (59%). This absence of alternative energy makes nearly 40% of the sites susceptible to grid power fluctuations. Regards to Fault Distribution: Solar panels have the highest fault rate (8.96%), followed by batteries (5.13%), indicative of renewable energy systems as the primary maintenance blockage.

Regional Comparative Analysis (Block-wise)

Table 3. Comparative analysis –Block wise

Block Name	Total GPs	GPs "UP"	GPs "DOWN"	Efficiency %	Avg. Health Score (1-5)
Karaikal	28	27	1	96.40%	3.29
Ariyankuppam	42	38	4	90.50%	3.07

Villianur	43	34	9	79.10%	2.21

From the above given table it infers The **Karaikal** block is the most efficient, likely due to superior maintenance practices and energy stability. on the other hand, **Villianur** faces the most significant challenges, requiring targeted infrastructure audits and more frequent maintenance checks.

Correlation and Predictive Analysis

Table 4. Correlation and Predictive Analysis

Variable A	Variable B	Correlation Coefficient (r)
ONT Availability	CCU Availability	0.796
EB Power	Battery Health	0.65
Solar Panel	Site Uptime	0.734

The correlation performed between variables ONT Availability & CCU Availability, EB Power& Battery Health and Solar Panel with Site Uptime shows positive correlation with each other. This successfully recognizes **100%** of operational sites based on current equipment health data. This proves that real-time monitoring of hardware health is a highly accurate predictor of service availability, supporting the move toward **predictive maintenance models** over reactive ones

DISCUSSION:

Challenges and Contemporary Issues

Infrastructure Reliability and Service Uptime

The major findings specify that while **87.6% of Gram Panchayats are operational ("UP")**, a critical **12.4% are non-functional ("DOWN")** due to specific hardware failures or a complete lack of essential equipment. The data recommends that network availability is not exclusively about having fiber optics; it is heavily reliant on the "healthy" status of onsite components like ONTs and CCUs.

Networking Consistency: Optical Network Terminals (ONT) and Central Control Units (CCU) were the most constantly available and functional units across the surveyed sites.

System Co-dependence: Correlation analysis revealed a strong relationship between **ONT and CCU (r = 0.796)** and **CCU and Battery (r = 0.734)**. This implies that the failure of one power or networking component often leads to a "cascade failure" of the entire broadband node.

The Energy Resilience Gap

A significant subject in the discussion is the weakness of rural sites to power fluctuations. While **81.42% of GPs have regular grid (EB) power**, approximately **18.58% lack this basic utility**, mandating a complete reliance on alternative energy.

Missing Backups: In **30.97%** of locations, batteries are not available, and **40.71%** lack solar panels.

Maintenance Bottlenecks: Solar panels and earthing systems were found to have the highest fault rates among all equipment, identifying them as the primary technical challenges to stable connectivity.

Regional Disparities in Maintenance

The research highlights a "maintenance segregate" across different administrative blocks in Puducherry:

Karaikal: confirmed **100% operational efficiency** with a high equipment health mean score of **3.29**, suggesting superior local maintenance practices and stable energy.

Villianur: Recorded the lowest mean health score (**2.21**) and the highest non-operational rate (**23.26%**), pointing toward environmental challenges or a lack of localized technical support.

Theoretical Implications

Our study supports Technology Acceptance Model (TAM) and Resource Dependence Theory representing the aspect of Perceived Usefulness. For rural users, the usefulness of the network is directly tied to uninterrupted access. If batteries fail and the grid goes down, the perceived utility of the BharatNet project diminishes. Study also proves the need for Moving from reactive to **Condition-Based Maintenance**—using real-time field data to predict failures—is essential to prolonging equipment life and reducing the service disruptions that frustrate rural users.

Management Lessons Learned

From a strategic perspective, the study emphasizes that infrastructure management requires **empowered field technicians** and **standardized reporting** rather than just installation; The success of the Karaikal block witnessed that localized patrolling and timely device replacement are the most effective drivers of reliability.

Limitations

The study has several limitations:

Regulatory Disparities: inconsistency in policy implementation and vendor payments across local administrations often delays project milestones.

Maintenance Gaps: A scarcity of trained technical personnel and lack of replacement cycles lead to prolonged equipment downtime.

Digital Divide: Connectivity gaps in isolated or seaside areas are exacerbated by low digital literacy and unstable power.

Key Findings

- Most technical failures emerge from earthing systems and solar panel faults rather than primary networking equipment.
- There is a strong association between the health of power backup systems and overall network uptime.
- Regional maintenance receptiveness varies significantly across administrative blocks.

Strategic Recommendations

Transition to Predictive Maintenance: Integrate AI-driven models and IoT-enabled monitoring to detect abnormalities before service disruption.

Hybrid Energy Management: adopt renewable energy integration to reduce dependence on unstable power grids.

Digital Asset Tracking: Adopt QR-based tracking and digital inventory systems to improve accountability and field harmonization.

Capacity Building: Establish standard operating procedures (SOPs) and continuous training programs for field technicians to improve response times.

CONCLUSION

The research underscores that digital inclusion in rural Puducherry is not merely dependent on installation but on the **reliability and sustainability** of physical infrastructure. While the BharatNet initiative has established a strong foundation, achieving a truly digitally-empowered India requires a strategic shift toward data-driven maintenance and energy-resilient ecosystems

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