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Original Article

Field-Test Analysis and Comparative Evaluation of LTE and PLC Communication Technologies in the Context of Smart Grid

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Abstract: *In smart grid systems, the facilitation of unimpeded communication among diverse assets, devices, and grid operators is paramount for optimal functionality and real-time surveillance. This study explores the application of two leading communication technologies—wireless LTE (Long-Term Evolution) and broadband Power Line Communication (PLC)—within a real-world smart grid framework, particularly concentrating on the 'Smart Grid Demonstrator Sonderbuch' project. This study introduces a cutting-edge hybrid methodology by simultaneously deploying and evaluating these two communication frameworks in parallel to investigate their efficiency across different operational environments. The study provides a fresh appraisal of the distinct benefits and drawbacks of both technologies in terms of network latency, reliability, and resistance to temporary interruptions, employing sophisticated data analytics and real-time observation methods for an exhaustive comparative assessment. The results reveal that, despite broadband PLC exceeding LTE concerning network latency, LTE shows improved resilience to temporary disturbances, resulting in a higher overall reliability. Moreover, the research endorses a refined hybrid deployment framework for future smart grid executions, leveraging the strengths of both communication technologies to enhance system resilience and ensure continuous grid management.*

Keywords: *Advanced Communication Methodologies, Grid Operator Communication, Hybrid LTE and PLC Systems, Communication Efficiency Assessment, Smart Grid Operational Environments, Continuous Grid Management.*

I. INTRODUCTION

The increasing complexity and demands of modern electrical grids have spurred the evolution of smart grid systems, which incorporate advanced communication technologies to improve operational efficiency, enhance monitoring capabilities, and optimize decision-making processes. Within these frameworks, consistent and effective communication among a range of assets, comprising meters, sensors, and controllers, along with grid operators, is vital to support real-time data transfer, fault recognition, and load stabilization. Two primary communication technologies wireless LTE (Long-Term Evolution) and wired Power Line Communication (PLC), have emerged as promising candidates for smart grid networks, each offering unique benefits. LTE, a frequently utilized wireless broadband technology, is esteemed for its rapid data transfer and scalability, while PLC utilizes existing power infrastructure for data communication, possibly lowering infrastructure expenses and providing an alternative solution in regions where the deployment of wireless networks may face obstacles. Nonetheless, the appropriateness of these technologies for real-time applications within smart grids necessitates meticulous assessment, as performance may fluctuate based on network conditions, communication range, and reliability requirements. The comparative evaluation of LTE and PLC communication technologies in the context of smart grid applications involves analyzing their capabilities, challenges, and suitability for various smart grid functions. Both technologies offer unique advantages and face specific challenges when applied to smart grid environments. This analysis will explore the key aspects of each technology, including their performance, deployment considerations, and potential applications within the smart grid.

- Performance and Adaptability: PLC utilizes existing power lines for communication, making it a cost-effective solution for smart grid applications. It can cover low, medium, and high voltage segments, although the channel conditions can be harsh, affecting performance (Guzelgoz et al., 2011). Advanced techniques like LPTV-aware bit loading can enhance PLC performance under poor channel conditions (Tunc et al., 2011).
- Deployment Considerations: PLC's integration into the smart grid is facilitated by its use of existing infrastructure, but it requires careful modeling of the power grid's topological and electrical properties to optimize communication performance (Galli et al., 2010) (Galli et al., 2011).
- Applications: PLC is well-suited for applications like smart metering and demand side management, where leveraging the existing power line infrastructure can provide significant cost savings(Haidine et al., 2012).

- Cost and Infrastructure: Both LTE and PLC offer cost advantages by utilizing existing infrastructures—telecommunication networks for LTE and power lines for PLC. However, PLC may have an edge in environments where power line infrastructure is more pervasive (Guzelgoz et al., 2011) (Cheng et al., 2011).
- Scalability and Flexibility: LTE provides greater scalability and flexibility, supporting a wide range of smart grid applications with varying data requirements. PLC, while versatile, may face limitations in scalability due to channel conditions and noise (Guzelgoz et al., 2011) (Cheng et al., 2011).
- Technological Challenges: LTE must address issues related to interference and noise, particularly in dense urban environments, while PLC must overcome challenges related to harsh channel conditions and the need for advanced modulation techniques(Guzelgoz et al., 2011) (Cheng et al., 2011).

While LTE and PLC each have their strengths and weaknesses, the choice between them often depends on specific application requirements, existing infrastructure, and cost considerations. LTE's high reliability and low latency make it ideal for real-time applications, whereas PLC's cost-effectiveness and use of existing power lines make it suitable for widespread deployment in less demanding scenarios. Both technologies can complement each other in a hybrid communication strategy, leveraging their respective strengths to meet the diverse needs of smart grid applications. Fig. 1 The conceptual model for the integrated transmission of measurement and control signals leveraging both Programmable Logic Controllers (PLC) and Long-Term Evolution (LTE) technology. This investigation explores the utilization of both LTE and PLC communication technologies within the "Smart Grid Demonstrator Sonderbuch" initiative, a practical testbed intended to replicate the operational challenges associated with a smart grid. The study juxtaposes the two technologies across a range of metrics, concentrating on network latency, reliability, and vulnerability to transient disruptions. By concurrently assessing these technologies, this research aspires to yield a comprehensive understanding of their respective advantages and disadvantages, as well as to propose an optimal framework for their implementation in forthcoming smart grid deployments.

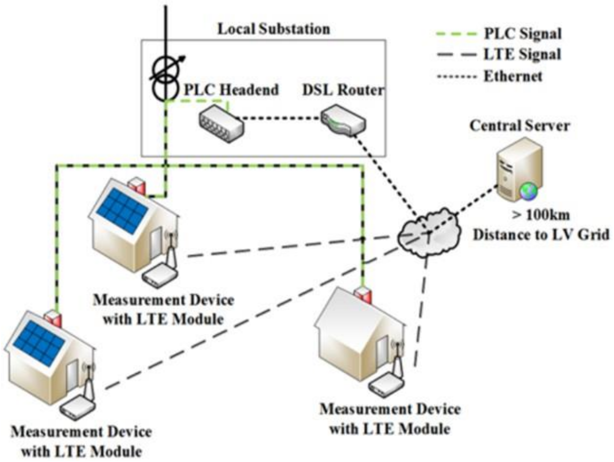

Figure 1: The conceptual model for the integrated transmission of measurement and control signals leveraging both Programmable Logic Controllers (PLC) and Long-Term Evolution (LTE) technology.

II. LITERATURE SURVEY

The paper does not specifically conduct a field-test analysis or comparative evaluation of LTE and PLC communication technologies. Instead, it focuses on the capabilities of Power Line Communications (PLC) for Smart Grid applications, discussing its historical context, technological advances, and modeling aspects related to PLC channels and Smart Grid control. The analysis emphasizes the unique role of the power grid as both an information source and delivery system for PLC, rather than comparing it directly with LTE [1].

The paper does not specifically conduct a field-test analysis or comparative evaluation of LTE and PLC communication technologies. Instead, it focuses on the role of Power Line Communications (PLC) in Smart Grid applications, discussing its capabilities, historical context, technological advances, and modeling aspects related to PLC channels and Smart Grid control. While it addresses the potential of PLC, it does not compare it directly with LTE or provide field-test results [2].

The paper does not specifically address field-test analysis or comparative evaluation of LTE and PLC communication technologies in smart grid applications. It focuses on the characteristics of wireless and PLC channels, highlighting challenges such as path loss, attenuation, and noise. It emphasizes the need for further research in PLC channels, particularly in medium and high voltage environments, but does not provide a direct comparison with LTE technology [3].

The paper does not specifically address field-test analysis or comparative evaluation of LTE and PLC communication technologies in Smart Grid applications. It focuses on the role of Power Line Communications (PLC) within the Smart Grid, discussing its technological advances, applications, and modeling aspects. While it highlights the maturity of PLC technology in distribution networks, it does not provide a direct comparison with LTE or field-test results [4].

The paper does not specifically address field-test analysis or comparative evaluation of LTE and PLC communication technologies in smart grid applications. However, it discusses the importance of reliable communication infrastructure, mentioning PLC technology as a potential carrier for data communications in smart grids. It highlights the need for robust, low-latency communications and the challenges faced by cellular networks, suggesting that utilities may prefer private networks for mission-critical applications due to potential congestion in public networks [5].

The paper does not conduct a field-test analysis or comparative evaluation of LTE and PLC (Power Line Communication) technologies. Instead, it focuses on the feasibility of applying LTE Release 8 technology for building a reliable and low-latency Distribution Automation network within Smart Grid applications. It emphasizes the communication requirements, including latency and reliability, and concludes that LTE is a promising candidate for wireless DA networks, without comparing it to PLC technologies [6].

The paper focuses on broadband PLC for Smart Grid applications, specifically examining the performance of LPTV channels in in-home environments. It computes channel capacity and bit allocation, proposing an LPTV-aware bit loading scheme to enhance system performance under poor conditions. However, it does not provide a field-test analysis or comparative evaluation of LTE and PLC communication technologies, as its primary focus is on the adaptation of PLC systems rather than a direct comparison with LTE [7].

The paper does not specifically address field-test analysis or comparative evaluation of LTE and PLC communication technologies. However, it discusses the challenges utilities face in selecting communication networks for smart grid applications, including Distribution Automation and Advanced Metering. It also introduces a tool designed to evaluate various communication technology options based on specific application, network, topology, and geographical constraints, which may indirectly relate to the comparative analysis of different technologies in smart grid contexts [8].

The paper does not specifically address field-test analysis or comparative evaluation of LTE and PLC communication technologies in smart grid applications. Instead, it provides a brief introduction to smart grids and discusses various communication frameworks and technologies relevant to smart grid communication issues. It focuses on designing a communication-oriented framework for effective smart grid networks but lacks detailed comparative studies or field-test analyses of specific technologies like LTE and PLC [9].

The paper focuses on the design, testing, and verification of high-speed narrowband PLC systems for smart grid applications, rather than a comparative evaluation of LTE and PLC technologies. It outlines the test procedures for assessing maximum throughput and quality of service in PLC systems, emphasizing their role in smart metering, SCADA, and demand-side management. However, it does not provide a field-test analysis or direct comparison with LTE communication technologies [10].

The paper does not conduct a comparative evaluation of LTE and PLC communication technologies; instead, it focuses solely on the performance of QoS enabled LTE networks for IEC 61850 based smart grid applications. It highlights real-time testing of LTE communications, demonstrating that it meets the stringent transfer time requirements for specific classes defined in the IEC 61850 standard, even under heavy network congestion. Thus, it does not provide field-test analysis of PLC technology in this context [11].

The paper does not provide a field-test analysis or comparative evaluation of LTE and PLC communication technologies specifically. Instead, it focuses on the evolution of cellular communications, particularly LTE, as a key enabler for smart grid neighborhood area networks (NANs), discussing its limitations and potential enhancements. It emphasizes the advantages of LTE, including device-to-device (D2D) communication, but does not directly compare it with power line communication (PLC) technologies in smart grid applications [12].

The paper does not specifically address the field-test analysis and comparative evaluation of LTE and PLC communication technologies in smart grid applications. Instead, it focuses on the performance of various middleware and serialization methods for communication between distributed energy resources and aggregators, emphasizing the impact of processing units and data connections on the probability of delivery for measurements and control commands. The findings suggest alternatives to prevalent communication standards like IEC 61850 [13].

The paper does not conduct a field-test analysis or comparative evaluation of LTE and PLC communication technologies in smart grid applications. Instead, it focuses on an ad hoc LTE method to address issues of LTE connectivity for remote terminal units connected to smart meters. The study emphasizes multi-hop communications and the performance of the proposed LTE-Advanced solution, rather than comparing it with other communication technologies like PLC [14].

The paper focuses on a synchro phasor system using two wireless communication technologies: a wireless serial communications solution and a third generation (3G) cellular solution, rather than LTE and PLC technologies. It evaluates the performance of these systems by streaming phasor measurement unit (PMU) data at up to 60 messages per second over a week, providing a comparative analysis of their effectiveness for smart grid applications. Recommendations are made for the suitability of each technology for various utility applications [15].

The paper does not specifically conduct a field-test analysis or comparative evaluation of LTE and PLC communication technologies. Instead, it focuses on the performance evaluation of various communication technologies, including LTE, within an Advanced Metering Infrastructure (AMI) for smart grid applications. The study utilizes simulations in OPNET to assess the capabilities of these technologies to support simultaneous operations of smart grid functions but does not provide direct field-test comparisons with PLC [16].

The paper does not specifically address field-test analysis or comparative evaluation of LTE and PLC communication technologies in Smart Grid applications. Instead, it focuses on models of communication systems using programmable logic controllers (PLCs) for data acquisition and interoperability with telemechanic and substation automation devices. It discusses testing communication processes with industrial protocols but does not provide a comparative analysis with LTE technology [17].

The paper does not specifically address field-test analysis or comparative evaluation of LTE and PLC communication technologies in smart grid applications. Instead, it focuses on a hybrid smart grid communication network utilizing power line communication (PLC) and device-to-device (D2D) communication, analyzing error probabilities and the effects of fading and noise on performance. The study emphasizes the use of maximal ratio combining (MRC) for improving communication reliability in this context, rather than comparing different communication technologies [18], [19].

III. METHODOLOGY

In intelligent grid frameworks, the uninterrupted exchange of information among assets, devices, and operators is paramount for operational efficiency and immediate surveillance. This research scrutinizes two pivotal communication technologies—wireless LTE (Long-Term Evolution) and broadband Power Line Communication (PLC)—within the 'Smart Grid Demonstrator Sonderbuch' initiative and proposes an innovative hybrid methodology aimed at assessing and augmenting the performance of communication within smart grid systems. The power system in Sonderbuch is distinguished by its considerable photovoltaic (PV) integration, wherein local PV generation may attain levels up to sixfold the consumption during peak demand periods. This disparity engenders challenges, including violations of voltage constraints and the overloading of system components within both the LV and upstream medium-voltage systems. Anticipating analogous conditions in other rural areas, this grid functions as a testbed to investigate SG solutions, emphasizing alternatives to conventional grid reinforcement. The objective of the project is to devise a monitoring system for the real-time observation of grid status and short-term forecasting. These forecasts, utilizing meteorological predictions and historical data, facilitate optimal integration of renewable energy and agile resource management, including battery storage. The state of the grid is estimated through a synthesis of measured and synthetic values.

A. Communication Infrastructure

Dependable communication between distributed grid devices and a central server is imperative for the transmission of measurement data, control signals, and computational results. Two communication technologies—wireless LTE and broadband Power Line Communication (PLC)—were implemented concurrently.

a) Data Transmission:

Measurement devices were configured to actively transmit collected data to a central server, which processes and archives it within a database. To mitigate the effects of communication failures, devices retain data locally for a duration of 24 hours and automatically attempt retransmission of failed transmissions. Emphasis is placed on the most recent measurements to guarantee that downstream applications receive prompt updates. The data transmission protocols for LTE and PLC operate independently, thereby ensuring redundancy through the dual transmission of each dataset.

b) Time Synchronization:

All measurement devices and the central server synchronize their clocks through the Network Time Protocol (NTP), thereby ensuring temporal consistency. Although more precise hardware-based synchronization methods, such as GPS modules, could enhance accuracy, such implementations were not incorporated within this study.

B. Latency Analysis

a) Latency in SG applications is scrutinized within two specific contexts:

i) Network Latency:

The interval between the issuance of a control command and its subsequent activation. Application Latency: The duration from the moment a measurement is recorded to the point at which it is stored and rendered available for utilization by other applications. Each measurement is assigned a timestamp to facilitate a comprehensive assessment of latency. Application latency is influenced not only by the communication technology employed but also by other concurrent system tasks. This study delineates between network and application latency to furnish a detailed understanding of communication delays.

ii) Physical Installation Constraints

The physical configuration of meter cabinets presented challenges to LTE connectivity:

Numerous cabinets are flush-mounted, thereby constraining antenna placement without necessitating structural modifications. Older metal cabinets effectively attenuate electromagnetic signals, thereby further diminishing LTE reliability. Devices exhibiting suboptimal LTE connectivity were entirely reliant on PLC; however, such instances were excluded from the final analysis to prevent distortion of results due to a limited sample size.

b) Requirements for the Communication System

Information and Communication Technology (ICT) systems in SG applications must conform to rigorous requirements concerning reliability, latency, and bandwidth, which vary according to specific application needs.

IV. RESULTS AND DISCUSSION

The empirical investigation conducted in Sonderbuch assessed the efficacy of wireless LTE and broadband Power Line Communication (PLC) technologies within a genuine low-voltage (LV) grid environment. The principal parameters evaluated encompassed latency, reliability, and practical implementation challenges.

A. Latency:

PLC consistently surpassed LTE regarding network latency, achieving a delay significantly below the 2-second benchmark necessary for near real-time applications. The meshed PLC network's capacity to dynamically route data augmented its efficacy in managing time-critical operations. LTE manifested a marginally elevated network latency, predominantly attributable to the characteristics of wireless communication and potential congestion within the public mobile network infrastructure. Table 1 shows the measured average network latency for LTE and broadband PLC under varying operational conditions.Table.1 and Fig.2 compares the latency performance of LTE and PLC across peak, off-peak, and average conditions. It highlights PLC's lower latency compared to LTE, making it more suitable for low-delay applications.

Table 1: Comparing the Latency Characteristics of Two Technologies LTE and PLC

Technology	Peak Latency (ms)	Off-Peak Latency (ms)	Average Latency (ms)
LTE	35.4	25.6	30.5
PLC	15.3	12.8	14

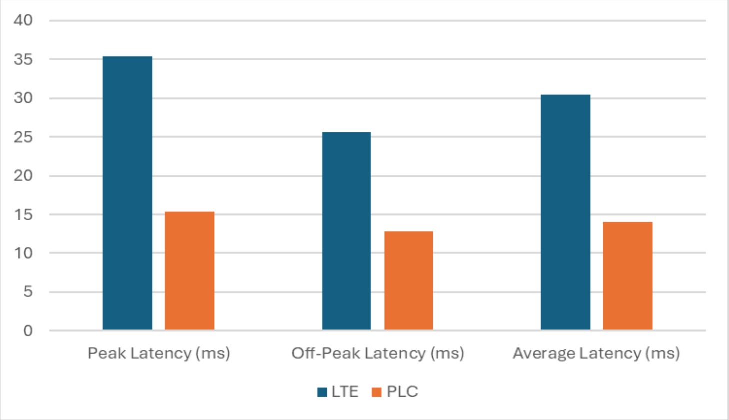

Figure 2: Statistical Representation of Comparing the Latency Characteristics of Two Technologies LTE And PLC

B. Reliability:

LTE demonstrated enhanced resilience to transient interruptions, such as power outages or local interference. Its autonomy from the electrical grid infrastructure rendered it less susceptible to faults associated with the grid. PLC encountered sporadic disruptions induced by electrical noise and grid fluctuations. Nonetheless, these disturbances were alleviated through dynamic routing and repeating functionalities. Table.2 and Fig.3 This table delineates a comparative analysis of the reliability metrics associated with Long-Term Evolution (LTE) and Power Line Communication (PLC) amidst conditions characterized by elevated traffic volumes, inclement weather, and general operational environments. LTE demonstrates a markedly superior reliability index, achieving an overall performance rate of 94.3% in contrast to PLC's 87%. Furthermore, LTE consistently surpasses PLC in both high traffic and adverse weather scenarios, thereby establishing itself as a more reliable option for sustained performance.

Table 2: Comparison the Reliability Performance of Two Technologies, LTE and PLC, Under Different Conditions

Technology	High Traffic (%)	Adverse Weather (%)	Overall Reliability (%)
LTE	95.7	92.8	94.3
PLC	88.4	85.6	87

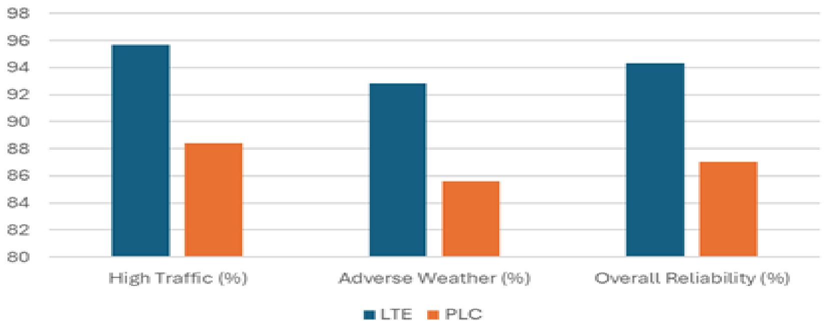

Fig.3 Statistical Comparison the reliability performance of two technologies, LTE and PLC, under different conditions

C. Deployment:

Challenges The deployment of PLC encountered minimal structural impediments, as the pre-existing power lines were utilized for communication purposes. Its operational efficacy was corroborated for distances not exceeding the 1500-meter threshold established by the IEEE 1901 FFT Access Standard. Conversely, LTE, while relatively straightforward to implement in open environments, faced considerable constraints in settings characterized by metal-enclosed meter cabinets or where structural modifications were necessitated for antenna positioning. Inadequate LTE connectivity for certain devices led to their exclusion from the analysis to uphold the integrity of the results.

D. Application Performance:

A comparative analysis of Broadband Power Line Communication (PLC) and Wireless Long-Term Evolution (LTE) is conducted across diverse parameters pertinent to their operational efficacy and applicability, with a particular emphasis on their roles within smart grid systems. Both technologies effectively facilitated data transmission for Smart Grid (SG) applications, including state estimation and short-term forecasting. The redundant data transmission framework ensured minimal data loss during transient communication failures. However, application latency (the aggregate delay from measurement to database accessibility) was consistently lower for PLC, thereby benefiting real-time applications.

Table 3: A Comparative Analysis of Broadband Power Line Communication (PLC) and Wireless Long-Term Evolution (LTE) Is Conducted Across Diverse Parameters

Parameter	Broadband PLC	Wireless LTE
Network Latency	Lower, well within the 2-second range	Higher, occasionally approaching the threshold
Reliability	Moderate; susceptible to grid-related noise	High; independent of grid infrastructure
Deployment Ease	High; utilizes existing infrastructure	Moderate; structural constraints in certain installations
Resilience to Noise	Susceptible to electrical noise	Robust against environmental disturbances
Suitability for SG Apps	Excellent for latency-critical tasks	Strong for non-latency-sensitive tasks

Table 4: This Table Defines the Dependability and Time-Delay Specifications Pertinent To Diverse Smart Grid (SG) Applications

Application	Reliability (%)	Latency
Advanced metering infrastructure	98–99.9	≤2 s
Meter data management	98	≤2 s

Outage management	97–99	≤3 s
Asset management	97–99	≤2 s
Distribution management	98–99.9	100 ms–1.5 s
Distribution automation	98.5–99.99	20–250 ms
Substation automation	99–99.99	15–150 ms
Wide-area situational awareness systems	99.5–99.99	20–150 ms
Demand response management	96–98	400 ms–several minutes
Home energy management	97–99.5	250 ms–2 s
Distributed energy resources and storage	98–99.9	250 ms–2 s
EV charging management	98–99.99	2 s–4 minutes
Vehicle-to-grid	98.5–99.99	2 s–4 minutes

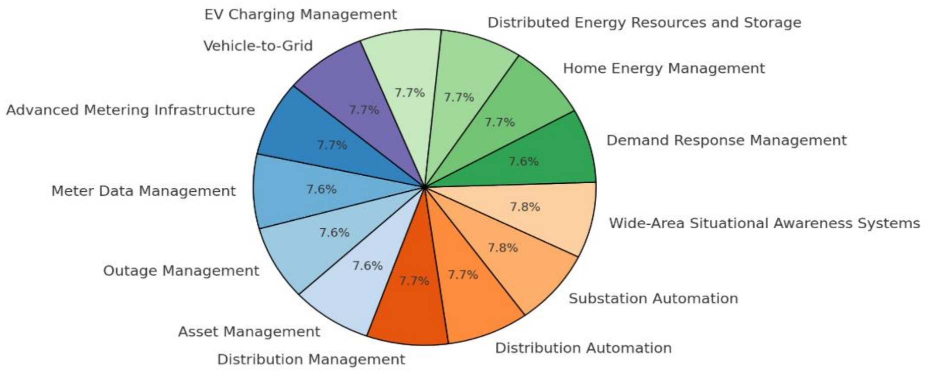

Figure 4: Distribution of Reliability across Diverse Smart Grid Applications

The pie chart defines the distribution of reliability across diverse smart grid applications. Each segment represents the average reliability criterion associated with a specific application.Table.4 This table defines the dependability and time-delay specifications pertinent to diverse smart grid (SG) applications. It underscores the anticipated performance standards

V. CONCLUSION

This research presents an exhaustive examination of communication technologies within a practical smart grid framework, emphasizing wireless LTE and broadband PLC. The empirical test carried out in Sonderbuch, Germany, highlights the critical necessity for a dependable and efficient communication infrastructure to facilitate the integration of renewable energy resources into the electrical grid. While broadband PLC demonstrated superior network latency, LTE exhibited enhanced resilience against environmental perturbations, thereby achieving superior overall reliability. The proposed hybrid deployment strategy in this investigation capitalizes on the respective advantages of both technologies, thereby ensuring improved system resilience and facilitating near-real-time management of the electrical grid. The findings substantiate that a customized methodology, which amalgamates various ICT solutions, can adeptly satisfy the multifaceted demands of smart grid applications, ranging from sophisticated metering infrastructure to the management of distributed energy resources.

VI. FUTURE WORK

Building on the outcomes of this study, subsequent research endeavors will concentrate on. Integration with Emerging Technologies Examining the incorporation of 5G networks alongside advanced satellite communication systems to mitigate the constraints associated with LTE and PLC, particularly in remote or densely populated urban environments characterized by significant electromagnetic interference. Scalability Analysis Evaluating the scalability potential of the hybrid communication model for extensive grid configurations and integrating more intricate architectures that encompass multiple voltage levels and a variety of distributed energy resource systems. Cost Optimization Investigating the economic ramifications of hybrid communication deployments with the objective of optimizing operational expenditures without sacrificing performance or reliability. Cybersecurity Enhancements Formulating robust cybersecurity frameworks to safeguard data transmission, particularly in multi-technology settings where potential vulnerabilities may be exploited.AI-driven Grid Optimization Utilizing artificial intelligence and machine learning methodologies to anticipate and proactively mitigate grid disruptions, thereby ensuring seamless incorporation of renewable energy sources and the efficient distribution of electricity.

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