Broadband PLC over Low Voltage Grid: Pilot Roll-out Results Assessment and Full Forecasting Roll-out

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***Abstract*— This project evaluates the deployment of hybrid BPL and PRIME v1.4 technologies in low-voltage grids across 68 secondary substations. The study evaluates the effectiveness of these technologies in improving grid reliability and data transmission, identifying key performance metrics and areas for improvement. The results highlight the potential of BPL technology to modernize power grids and provide real-time communication solutions.**

Keywords*— *Broadband Power Line, Low Voltage Networks, Smart Grids, Real-time Data Collection, PRIME v1.4.

I. Introduction

Powerline communication (PLC) technologies have become a crucial component in the implementation of smart grids by enabling data transmission over existing power lines. PLCs, in particular broadband power line (BPL) technology, enable efficient communication over power lines, making them a crucial tool for real-time monitoring and management of low-voltage grids. This project explores the deployment of hybrid BPL and PRIME v1.4 technologies in low-voltage grids, evaluating their performance and identifying key areas for improvement. By evaluating these technologies in 68 secondary substations, the project aims to provide data on the effectiveness of BPL in improving the reliability and responsiveness of modern power grids. The results contribute to the broader goal of developing more robust and scalable communication solutions in the power sector.

II. State of the Art

A. *Power Line Communications (PLC) Technologies*

Power Line Communications technologies have become an essential component for the implementation of Smart Grids by utilizing existing power lines for data transmission [1]. Although its penetration in the general telecommunications market is limited, PLC has been widely adopted in the energy sector due to its ability to provide services in areas where other technologies encounter difficulties or require large investments.

Historically, the first PLC applications emerged in the 19th century, focused on meter reading and voice communication. Later, in the 1950s and 1970s, systems for load management and automatic meter reading (AMR) were developed. Starting in 1990, standardization in Europe through the CENELEC EN 50065-1 standard organized the spectrum used for PLC applications, and advances in digital communication using orthogonal frequency division multiplexing (OFDM) techniques in the 2000s and 2010s enabled significant increases in bit rates without increasing bandwidth [1].

PLC works by dividing the spectrum into multiple subcarriers using OFDM modulation, which allows greater resistance to noise and interference. However, power lines are not designed for data transmission, facing problems such as signal attenuation, electromagnetic noise and variations in the properties of the medium [1]. To mitigate these problems, PLC employs advanced error correction techniques and adaptive modulation methods that dynamically adjust transmission parameters according to channel conditions.

B. *Narrowband PLC (NB-PLC)*

NB-PLC technology, which operates at frequencies between 3 and 500 kHz, was one of the first and most mature technologies in the field of PLC communications [1]. Within NB-PLC, low data rate (LDR) and high data rate (HDR) technologies can be distinguished.

1) Low Data Rates (LDR NB-PLC)

Low data rate technologies use single carrier modulation, achieving data rates down to a few kbps. These are mainly used in smart metering and home automation applications. Technologies such as Open Smart Grid Protocol (OSGP) and Meters and More have been adopted in several countries, offering standardized solutions for electrical substation automation and device-to-device communication [2].

2) High Data Rates (HDR NB-PLC)

NB-PLC HDR technologies employ multicarrier transmission, enabling data rates of up to a few Mbps. Notable examples include PRIME v1.3 and G3-PLC, both based on OFDM modulation [2]. These technologies have been widely deployed in several countries, improving the efficiency and robustness of smart grid communications.

PRIME v1.3, standardized as ITU-T G.9904, uses an OFDM transmission system with Fast Fourier Transform (FFT), channel coding and differential phase shift keying (DPSK) modulation, operating in the spectrum from 42 to 89 kHz. On the other hand, G3-PLC, defined by the G3-PLC Alliance, also uses OFDM modulation and adds capabilities such as dynamic carrier deactivation to avoid noisy bands [2].

C. *Broadband PLC (BPL)*

BPL represents an evolution of PLC technology, employing higher frequencies (above 2 MHz and up to 30 MHz or more) to transmit data at speeds of up to 250 Mbps. Unlike NB-PLC, BPL is used primarily in medium voltage (MV) networks, where conditions are more controlled and predictable than in low voltage (LV) networks.

1) Principal Standards

The development and adoption of BPL has been strongly influenced by several technical standards, each with its own characteristics and applications. The main standards governing BPL implementations are:

- IEEE 1901 [1] [2] provides high-speed communication solutions over existing power lines, making it suitable for both internal home networks and last mile access applications. It defines two different specifications for the PHY layer. First, FFT-OFDM PHY, which is based on HomePlug AV technology and uses OFDM modulation based on the FFT. In the 1.8-30 MHz band it uses 917 carriers out of the 1155 available, while in the 30-50 MHz band it uses 1974. On the other hand, the Wavelet-OFDM PHY specification uses Wavelet modulation instead of FFT, operating in the 0-30 MHz band and modulating 338 carriers out of the 512 available. The IEEE 1901 MAC layer employs a Master/Slave paradigm, where the Master coordinates the communication slots for the Slaves, thus managing network traffic and ensuring quality of service. It supports both CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) and TDMA (Time Division Multiple Access) to manage network traffic. IEEE 1901-2020 [3] standard introduced important improvements, including improved energy efficiency and better coexistence with other PLC technologies. These improvements are crucial in modern applications such as NESSUM, formerly known as HD-PLC, which optimises communications in high device density environments, offering a robust and scalable solution for smart grids and other industrial applications where reliability and performance are critical.
- IEEE 1901.1-2018 defines the technical specifications for the physical and MAC layers in broadband communication systems over power lines in the mid-frequency band below 12 MHz. The PHY layer uses OFDM to modulate the signals, splitting the band into multiple subcarriers, to improve robustness to noise and interference, and it also uses modulation adaptation and channel coding mechanisms that dynamically adjust transmission parameters according to channel conditions. The MAC layer mainly uses CSMA/CA to avoid collisions during data transmission, as well as includes mechanisms to manage the quality of service. Interoperability and coexistence with other IEEE 1901 standards are also considered, as well as coexistence with other PLC technologies by implementing interference mitigation techniques to ensure that different devices can operate simultaneously in the same environment without affecting communication quality [4].
- ITU G.hn standardized by ITU-T and promoted by the HomeGrid Forum Alliance, was initially developed for home networks, but has been adapted for use in distribution and smart metering networks. ITU G.hn can achieve speeds of up to 1 Gbps over various propagation media such as coaxial cables, telephone lines and optical fibre [5]. For the PHY layer it uses OFDM modulation in frequency bands up to 50 MHz or 100 MHz. It also includes a low complexity profile (LCP) for frequencies up to 25 MHz. It uses low-density parity control codes (LDPC) for error correction, increasing the robustness of transmission [5]. As for the DLL layer, it is defined in the ITU-T G.9961 recommendation, using multiple access mechanisms based on Time Division Multiple Access without contention and multiple access by carrier detection with collision avoidance. Data management is described in ITU-T G.9962, the application of Multiple Input Multiple Output (MIMO) procedures is specified in ITU-T G.996, and ITU-T G.9964 establishes power spectral density limits for transmitting devices operating at frequencies between 2 MHz and 30 MHz [5]. The MAC layer is based on TDMA and allows specific transmission times to be assigned to each device, ensuring efficient channel management and quality of service [5].
- OPERA (Open PLC European Research Alliance), funded by the European Commission, was launched in 2006 and uses OFDM-based signals with up to 1536 subcarriers and Amplitude Differential PSK modulation, achieving data rates of up to 200 Mbps [5]. For the PHY layer, it employs techniques such as adaptive modulation, frequency filtering and error correction codes such as Reed-Solomon and Trellis coded in four dimensions. While the MAC layer is based on TDMA, where a central device (head-end) controls the channel resources to ensure quality of service [5].
- NESSUM, formerly known as HD-PLC, has evolved through four technology generations, each adapting to different application scenarios. For the PHY layer, HD-PLC3 Complete is based on the IEEE 1901-2010 standard and uses the Wavelet-based PHY layer, achieving transmission rates of up to 240 Mbps. HD-PLC4, on the other hand, adapted the IEEE 1901-2010 standard to IEEE 1901a-2019, offering FCW channel options and an extended band from 31.25 MHz to 62.5 MHz, enabling transmission rates of up to 1 Gbps [5]. Moreover, for the MAC layer, the Multi-hop version includes hopping capabilities between network nodes, using the Centralized Metric-Based Source Routing (CMSR) protocol to progress the data signal between terminals connected to a master node [5]. Through the introduction of the IEEE 1901-2020 standard and the evolution to NESSUM, significant improvements have been incorporated that optimise spectral efficiency and coexistence with other technologies. NESSUM uses Wavelet-based OFDM, which not only improves spectrum efficiency, but also minimises interference, allowing flexible integration with other communication systems [3]. This is crucial in industrial and urban environments where device density and communication reliability are critical. In addition, NESSUM supports multi-channel communications and has extended its applicability to various platforms, including wireless and submarine communications, establishing itself as a robust and

scalable solution for smart grids and other advanced industrial applications.

- HomePlug standard, initiated in 2001, evolved from HomePlug 1.0 with data rates of 14 Mbps to HomePlug AV with rates of 200 Mbps using FFT-based OFDM [5]. On the physical layer, HomePlug AV2 (2012) supports MIMO and a wider frequency band (1.8 MHz-86.13 MHz), offering data rates up to 1.5 Gbps. For the MAC layer, it uses a hybrid TDMA/CSMA/CA configuration, ensuring efficient access to the medium and effective traffic management [5].

2) BPL over Medium Voltage

In medium voltage, the most widely used and most mature BPL technology is based on the OPERA specification. Proper network planning is essential to ensure optimal performance of BPL networks in MV, and OPERA technology has proven to be effective in large-scale deployments, implementing TDMA domains of limited size that coexist using an FDMA (Frequency Division Multiple Access) approach, ensuring non-interference between nearby TDMA domains [6].

To optimise the use of available frequencies, two main frequency modes are defined, Mode 1 that uses the 2 to 7 MHz range, and mode 2, which operates in the 8 to 18 MHz range [6]. Specific criteria must be followed to ensure adequate throughput and latency, such as limiting the number of substations in a cluster, controlling the number of hops between the master node and the slaves to keep latency within acceptable limits. The maximum distance that BPL links can reach should be defined conservatively, based on experience with European MV networks. Moreover, it is important to exclude customer-owned substations to avoid operational and maintenance problems [6].

In addition, BPL performance varies significantly between overhead and underground MV networks. Although overhead networks allow for easier signal propagation due to the absence of significant physical barriers, underground networks are preferred for BPL deployment for several factors [6].

Underground lines generally have direct paths between substations without intermediate branches, which improves signal quality. Furthermore, the shorter distances typical of underground lines allow controlled attenuation levels to be maintained, which is crucial for the integrity of data transmission. There is also greater immunity to interference from radio services, which is more common on overhead lines. The installation and maintenance of equipment in underground networks is safer and cheaper, as it does not involve working at heights, and urban areas with underground lines tend to have a higher density of meters, which maximises the return on investment in BPL infrastructure [6].

3) BPL over Low Voltage

Since the 1990s, utilities have used BPL in low-voltage networks for both internet access and smart grid services, primarily smart metering. European LV networks contain more complex topologies with more branching and sub-branching, which can cause signal reflections and affect transmission quality. In addition, limited budgets for LV network maintenance mean that there may be degraded cables affecting BPL signals. The lack of direct control over the loads connected to LV networks can lead to problems with unknown terminal impedances and noise levels, further complicating the effective implementation of BPL [7].

The planning and deployment of BPL in low-voltage networks requires careful consideration of several technical factors due to the inherent complexity and specific characteristics of these networks:

- Topological complexity [7]: European LV networks have a more complex topology with numerous branches and sub-branches, which can cause signal reflections. These reflections are particularly problematic at the high frequencies used by BPL, as they can cause interference and data loss. To mitigate these effects, signal equalisation techniques and low pass filters can be used. In addition, it is essential to perform a detailed network analysis to identify critical points where reflections may be more pronounced and apply specific solutions such as the use of repeaters or impedance adapters.

- Limited Maintenance Budgets [7]: Limited budgets for LV network maintenance mean that often only reactive rather than proactive maintenance is performed. This can result in degradation of cables and connections, negatively affecting the transmission of BPL signals. To meet this challenge, BPL implementation must be robust, using high quality components designed to operate in harsh conditions. In addition, a continuous monitoring system is implemented that can detect and report network failures or degradations for quick and efficient intervention.

- Controlling Variable Loads and Impedances [7]: In LV networks, the connected load can vary significantly over time and space, affecting the impedance of the network and thus the quality of the BPL signal. Variations in impedance can cause reflections and signal loss, making communication difficult. To mitigate this problem, advanced filtering technologies and noise mitigation techniques can be used, such as adaptive filters and robust modulation systems that can dynamically adjust to changing network conditions. Detailed network planning and modelling is also essential to anticipate and manage these variations.

- Network Noise [7]: LV networks are subject to high levels of electrical noise, generated both by connected devices and the network infrastructure itself. This noise can interfere with BPL signals, reducing the quality of communication. The implementation of noise-resistant channel coding and modulation techniques, such as Orthogonal Frequency Division Multiplexing, can help improve the resilience of the BPL signal, as well as the use of repeaters can strengthen the signal and improve coverage.

- Network Planning and Design [7]: The planning and design of a BPL network in the low voltage (LV) network requires a thorough approach to ensure optimal performance. However, it is crucial to emphasise that the LV network remains largely unknown, with significant gaps in knowledge and documentation. For many utilities, finding processable data that can be easily integrated into geographic information systems (GIS) to develop network topologies is neither common nor straightforward. This lack of accessible and accurate data reflects a broader problem of LV network neglect in many utilities. Therefore, careful selection of signal injection points, the use of suitable couplers and the implementation of a network topology that maximises coverage and minimises signal losses are essential. Detailed simulations and field testing are vital to validate the design prior to full deployment, although the success of these efforts is often hampered by the limited information available on the existing LV infrastructure.

D. Technological and Regulatory Challenges of BPL

The deployment of BPL faces technological, socioeconomic and regulatory challenges that must be addressed to ensure its viability and effectiveness.

1) Technological Challenges

- Radio Frequency Interference (RFI): RFI is a significant challenge for BPL, as signals in the 1.7 to 80 MHz range can interfere with licensed frequency bands, such as those used by amateur radios and emergency services. To mitigate this, guidelines have been established that include dynamic power reduction techniques and avoidance of specific frequencies [5].
- Grid Impedance: The impedance of the power grid varies depending on the topology and connected devices, which affects the propagation of PLC signals. These variations can cause mismatches that limit transmission efficiency. It is essential to accurately characterize impedance through extensive testing in different scenarios to improve power transfer [5].
- Noise and Non-Intentional Emissions (NIEs): Low voltage grids are exposed to high levels of noise and impulsive emissions generated by electronic devices, such as electric vehicle chargers and solar panels, which can significantly interfere with BPL communications. It is necessary to develop statistical models of network noise and employ advanced noise mitigation techniques [5].
- Transmission Losses: Transmission losses in the low voltage network increase with frequency, which limits the effective distance of BPL signals. Network branching generates additional losses that are difficult to model accurately. Characterization of network attenuation through field testing is crucial to determine optimal frequencies and maximum transmission distances [5].
- Channel Modelling: Accurate modelling of the transmission channel is essential for BPL implementation. Empirical approaches based on measurements and theoretical approaches based on transmission line theory should be combined to obtain a detailed model of signal propagation in the LV network, ensuring optimal band selection for signal-to-noise ratio (SNR) [5].
- Limitations of the Propagation Medium: The power grid is a hostile transmission medium due to the presence of interference, electrical noise and signal attenuation. It is necessary to develop detailed models of the network behaviour at the frequencies used by BPL and to implement advanced modulation techniques, such as OFDM and DSSS, to improve transmission robustness [5].
- Cybersecurity: The digitalization of the power grid increases its vulnerability to cyberattacks, so it is crucial to implement robust encryption techniques and advanced security protocols to protect sensitive consumption and grid quality data. It is also essential to develop methods to detect and mitigate attacks in real time [5].

2) Socio-economic Challenges

- Competition & Societal Issues: BPL technology may face competition and social acceptance issues, especially in areas where other broadband technologies are already established. The perception of BPL as a disruptive technology may generate resistance. There is a need to promote the unique advantages of BPL, such as its ability to provide Internet access in rural and unserved areas. In Australia, innovative broadband technologies such as BPL have been encouraged to bridge the digital divide, allowing commercial trials if they do not adversely affect legitimate spectrum users [8].
- Cross Subsidies: There is concern that electric utility revenues could be used to subsidize BPL prices, which could provide an unfair advantage to electric utilities (if they are monopoly suppliers of electricity in that area) and divert resources from the provision of electricity. In the United States, federal and state regulators have examined the problem of cross-subsidization, in several cases requiring companies to establish separate subsidiaries to ensure fair competition and prevent electric utility revenues from subsidizing BPL operations [8].

3) Regulatory Challenges

- Industry Governance Issues: Coordination between electricity and telecommunications regulators is crucial to avoid unnecessary regulatory hurdles in BPL deployment. Lack of coordination can lead to duplication of effort and inconsistencies that hinder implementation. The FCC has established rules to protect against radio frequency interference (RFI) and has created public databases to address these issues, requiring BPL devices to use adaptive mitigation techniques and maintain public records on location and frequencies used. The European Commission has also tasked standards bodies, such as ETSI and CENELEC, to develop harmonized electromagnetic compatibility (EMC) standards to ensure that BPL systems do not interfere with other users of the radio spectrum [8].
- Regulatory Classification & Treatment Issues: One of the main regulatory challenges is the lack of clarity in the classification and treatment of BPL within existing regulatory frameworks. In many countries, utilities can become telecom service providers using BPL infrastructure, but this requires

a favourable regulatory environment. In the US, the FCC has classified BPL as an "information service," which exempts it from certain open access requirements applicable to other forms of telecommunications. In Europe, BPL is regulated under the same rules as telecommunications networks under the Telecommunications Framework Directive 2002/21/EC, which involves complying with rules such as local loop unbundling and number portability to promote competition in the sector. The European Commission has recommended removing unjustified regulatory obstacles to BPL deployment, ensuring that networks comply with harmonized rules to avoid interference with other spectrum users. In addition, access to physical infrastructure such as poles and ducts is essential for BPL deployment, although in some regions utilities have avoided this regulation by not allowing communication services over their poles [8].

E. *Relevant Case Studies of BPL*

This section discusses several projects that implement BPL technology to improve the management and operation of power grids. Three main projects are highlighted: the use of BPL in medium-voltage grids as a multi-service backbone, E.ON's project in Germany to integrate BPL into the low-voltage grid, and a series of use cases standardized by the PRIME Alliance to validate the effectiveness of BPL in different contexts. These projects demonstrate the ability of BPL to provide real-time, secure communication and handle large volumes of data in modern energy infrastructures.

1) BPL Over Medium Voltage As Multiservice Backbone

This study focuses on the deployment of thousands of BPL links in medium voltage networks to provide smart grid services, demonstrating high technological resilience and operational efficiency. The BPL network design was adapted to the specific characteristics of the medium-voltage grid, validating the criteria through a pilot in a representative area [6].

Approximately 14,000 BPL devices were installed, achieving transfer rates of 30 to 50 Mbps with latencies of 10 to 20 ms per BPL hop. These results confirm that BPL can provide reliable and efficient performance in medium voltage networks [6].

2) E.ON Uses Corinex BPL

In 2018, E.ON, one of Europe's leading power grid and energy solutions companies, initiated a project to integrate BPL technology into its low-voltage grid in Germany [9]. The main motivation for this project was to ensure real-time communication between smart meters and the grid, while guaranteeing the safety and efficiency of the system.

The project was based on Corinex's BPL technology, using MaxLinear chips and the IBM Tivoli network management solution, and adopted the ITU G.hn standard. During the first two years, a pilot phase was carried out involving the deployment of approximately 10,000 repeaters and headends, covering hundreds of thousands of homes [10]. The results of this phase demonstrated that the technology met the necessary requirements for smart metering services.

The digitalization solution implemented by E.ON, based on BPL, provided reliable and secure communication, which is crucial for a flexible and resilient grid. Unlike centralized communication infrastructures using NB-PLC, the decentralized network with BPL enabled multidirectional communication, enhancing the network's ability to dynamically balance load and power generation through real-time energy data, analytics, and predictive modeling [10].

Figure 1.Centralized vs self-regulating digitalized grid [10].

This project highlights BPL's ability to overcome the limitations of NB-PLC technology, which is prevalent in many global markets, by offering a superior and more cost-effective connection. In addition, the project with Corinex not only validated the viability of BPL technology for smart metering, but also promoted a more efficient, secure and adaptable power grid for modern energy challenges.

3) Other BPL Use Cases

The cases presented below underscore how BPL can improve the management and operation of power grids, providing robust and flexible solutions to contemporary challenges in the energy sector.

- BPL Smart Meters with BPL Concentrator: This use case, adopted by ČEZ Distribuce, shows the combination of BPL with machine learning algorithms for predicting residential loads and solar production, optimizing grid efficiency [11].
- Coexistence of BPL and NB-PLC: This approach, tested by Iberdrola, facilitates the transition to more advanced technologies by allowing the coexistence of BPL concentrators with the installed base of NB-PLC smart meters, without the need to completely replace the existing infrastructure [11].
- BPL Smart Meter Gateway with Voltage Detection: Led by E.ON, this use case emphasizes the importance of voltage sensing to identify network problems, improve service quality, and reduce equipment investment [11].
- BPL on MV Lines: Iberdrola has implemented BPL on its medium voltage lines, demonstrating its ability to handle large volumes of data and support advanced applications such as demand response and electric vehicle integration [11].

III. PROJECT DEFINITION

As power grids experience significant transformation driven by electrification, decarbonization, decentralization and the need for security, there is a growing demand for infrastructures capable of efficiently managing these loads. Moreover, the integration of renewable energy sources and battery storage systems introduces variability in power generation, requiring advanced monitoring and management solutions to maintain grid stability.

A. BPL in Low Voltage Networks: Opportunities and Challenges

In the current digital era, the demands on power grids are becoming increasingly complex. This project seeks to address these demands by evaluating and forecasting the deployment of BPL technology in low voltage grids. This solution aims to improve the efficiency, reliability and responsiveness of electrical distribution networks.

BPL offers a series of advantages that position it as a key solution for the modernization of power networks. Among its main benefits is the use of existing power lines for data transmission, which significantly reduces implementation costs and facilitates rapid adoption without the need for additional infrastructure. Additionally, BPL provides much higher bandwidth compared NB-PLC, achieving data transmission rates of between 150 and 250 Mbps. This capability is essential for handling large volumes of real-time information, such as data from smart meters and other network devices. BPL also offers low latency and high availability, which is key for smart grid applications that require immediate responses, such as demand-side management or the integration of renewable energy sources. By interoperating with existing technologies, such as PRIME, BPL enables a gradual transition without the need to completely replace the current infrastructure.

BPL is positioned as a key technology to enable the Smart Grid in low voltage networks, significantly enhancing the capabilities of narrowband PLC communications without adding cost to the current generation of smart meters. While it is possible that the next generation of smart meters will eventually support BPL, the current costs are unaffordable based on the current regulatory regime. However, the continued development and deployment of BPL technology, as pursued in this project, can stimulate the market and encourage the development of low-cost BPL solutions for future smart meters.

Despite its advantages, BPL also presents significant challenges. The transmission quality of PLC signals can be affected by the network infrastructure, especially in low-voltage networks with complex topologies and multiple branches, which can cause signal reflections and affect transmission quality. In addition, proximity to sources of electrical noise, such as household appliances or industrial machinery, can interfere with BPL signals, reducing their efficiency. Another major challenge is the variability in the load and impedance of low-voltage networks, which can cause signal losses and a decrease in communication reliability. To mitigate these problems, it is necessary to use advanced filtering and noise mitigation technologies, as well as to carefully plan the network to identify and correct critical points. Finally, underground networks require the installation of repeaters in accessible locations, which can increase the complexity and cost of implementation.

The regulatory framework is important in the adoption and deployment of BPL. European directives and global regulations drive the digitalization of power grids and promote the use of advanced technologies to improve grid management and sustainability. European Union Directive 2019/944, for example, sets the framework for modernizing the EU electricity market, obliging utilities to implement smart metering systems and improve demand response, facilitating the integration of distributed energy resources. The EU Action Plan on Digitalizing the Energy System (2022) reinforces this approach by promoting the creation of a "digital twin" of the power grid and establishing an international data exchange framework for the integration of renewable energy sources. In the United States, FERC Order 2222 (2020) encourages the integration of distributed energy resources (DERs) into wholesale electricity markets, requiring utilities to revise their market rules and tariffs to allow DER participation. These regulations not only drive the adoption of BPL, but also ensure that its implementation is aligned with the global goals of decarbonization and grid digitalization.

B. Hybrid Solution for the Low Voltage Network

The existing infrastructure, based on PRIME v1.3 technology and NB-PLC, has significant limitations in data transmission speed, making it difficult to effectively monitor and manage the network in real time. To overcome these limitations, the project proposes a hybrid solution that extends BPL technology from secondary substations to street fuse boxes (SFBs) and house connection boxes (HCBs), using Corinex BPL equipment, ITU G.hn technology and MaxLinear's ITU G.hn MIMO chip. This approach represents a significant improvement in data rates and real-time monitoring capabilities.

One of the main drivers for this project is the need for more frequent, accurate and higher volume data collection from smart meters, driven by both stringent regulatory requirements and increasing user demand for real-time access to their consumption data. Currently, smart meter data is collected every 15 minutes, creating unacceptable wait times for users who want to access their consumption information online. This creates an urgent need to reduce data collection times to less than 15 minutes to meet regulatory standards and consumer expectations.

Another key aspect of this project is the limited knowledge that utilities have of their own low-voltage networks. Due to the large number of connection points and the complexity of their topology, these networks are not fully surveyed or digitalized. To address this, the project has also focused on an algorithm that optimizes the deployment of BPL by determining the minimum distances between repeaters from the secondary substation.

To achieve all this, this project evaluates the effectiveness of Corinex's BPL technology, deployed in various secondary substations within the low voltage network, and to determine its suitability for wider deployment. It also assesses the performance of the BPL technology under real-world conditions, developing network optimization algorithms to calculate optimal distances between repeaters, and exploring alternative technologies if the Corinex solution does not meet the expected functionalities.

IV. Model Developed

The deployment of a hybrid architecture combining BPL and NB-PLC technologies in the LV low-voltage network is a key strategy to improve the efficiency and manageability of power grids. This model is being developed as part of an innovative project by i-DE, which aims to modernise the telecommunications infrastructure in electricity grids by extending BPL technology from secondary substations (SS) to street fuse boxes (SFBs) and house connection boxes (HCBs), while PRIME technology is used from SFBs to smart meters (SM).

Since 2010, i-DE's low-voltage network has used PRIME v1.3 technology for communication between secondary substations and house connection boxes. PRIME v1.3 is an NB-PLC technology that enables a bit rate of up to 128 kbps. This technology has been essential for measurement data collection and basic network management but has significant limitations in terms of data rate and the ability to handle large volumes of real-time information.

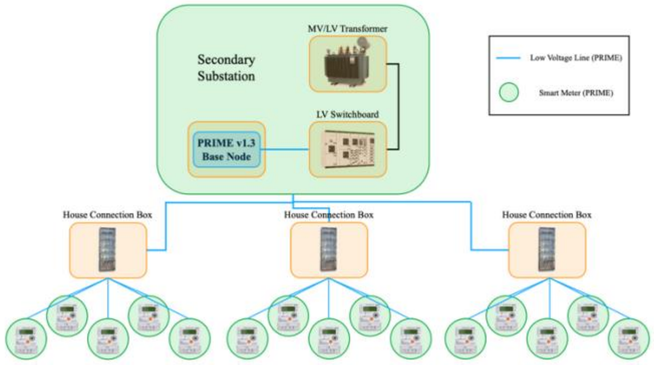

Figure 2. Actual Solution (100% PRIME v1.3).

The current model, which is represented in Figure 2, has a structure in which SS act as centralised collection points, connecting all smart meters through an extensive PRIME network. This configuration, while effective at the time, has proven to be insufficient for the growing demands of modern electricity grids, which require increased data transmission capacity and reduced latency to handle renewable energy integration and digitalization.

The new hybrid architecture, which can be observed in Figure 3, combines BPL with PRIME v1.4 to optimise data transmission and improve network efficiency. In this configuration, BPL extends from the secondary substations to the SFBs and HCBs, enabling data transmission at speeds in the Mbps range. From the SFBs, PRIME v1.4 handles communication with the smart meters.

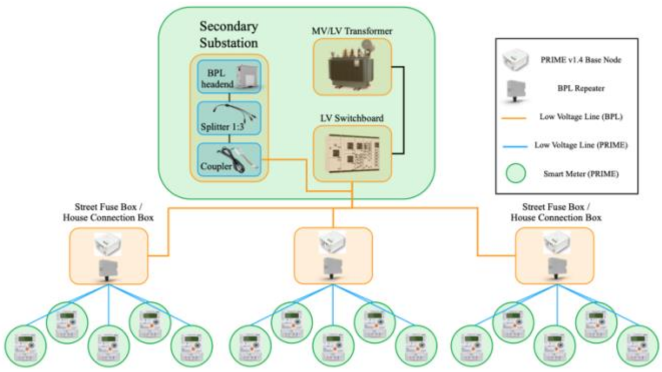

Figure 3. Hybrid Solution (BPL + PRIME v1.4).

The first part of the model involves the use of BPL technology from SS to SFBs or HCBs. BPL operates in a higher frequency range than NB-PLC, which allows significantly higher transmission rates, reaching speeds in the order of Mbps. This technology uses the ITU G.hn standard with MIMO (Multiple Input Multiple Output), which improves the network's ability to handle multiple data transmissions simultaneously, optimising the use of available spectrum and reducing interference.

In the implementation, a BPL master is installed in the secondary substation, and connected via USB-B ports to splitters that inject the BPL signal into the low voltage lines. This injection is done using AMI sensors or Niled connectors, depending on the substation specifications and conditions. BPL repeaters are installed at SFBs or at intermediate points in the network, such as on some lines within the secondary substation, to regenerate the signal and maintain its quality throughout the network.

From SFBs to smart meters, communication is performed using PRIME v1.4 technology, which is an evolution of the PRIME v1.3 standard. PRIME v1.4 offers significant improvements, including greater efficiency in network management and the ability to support smaller and less congested networks. This version enables simultaneous communication with all smart meters connected to a SFB, reducing latency and improving network response speed.

Unlike the previous version, PRIME v1.4 can divide the network into smaller units using different frequency bands, where each SFB acts as a base node for a small group of smart meters, rather than connecting hundreds of meters to a single secondary substation. This not only improves network efficiency, but also facilitates management and maintenance, as problems can be isolated and resolved more quickly in smaller, localised networks.

The main benefit of this hybrid architecture is the ability to handle large volumes of data with high speed and low latency. The combination of BPL and PRIME v1.4 enables a significant improvement in data transmission, which is essential for real-time management and regulatory compliance. In addition, the reduction in the number of nodes in each PRIME network and the improved signal quality thanks to BPL technology contribute to more efficient network operation. The ability to perform simultaneous and rapid readings of smart meters improves demand management and energy distribution, resulting in a more stable and reliable grid.

While hybrid architecture offers numerous benefits, it also faces significant challenges. Those challenges include the coordination of diverse technologies and equipment, as well as compatibility between existing infrastructures and new technologies. The transition from a PRIME v1.3-based NB-PLC network to a hybrid architecture also requires planning and possible device upgrades.

V. Tools for Performance Analysis

Following the selection of 70 secondary substations (SS), Corinex BPL technology was deployed in them, following the model described above. To analyse the performance and operation of this technology, several key tools were used: MapInfo, Grafana and GridValue.

A. *MapInfo Professional 12.0*

MapInfo Professional 12.0 is the geographic information systems (GIS) software used by Iberdrola to manage and analyse electrical and telecommunications infrastructures in Spain. This software allows the visualization and graphical management of all telecommunications assets through the SICOID tool, an Iberdrola customization of General Electric's GIS platform, Smallworld. It also integrates with SIGRID, another GIS system that enables visualization of electrical networks, providing a unified perspective of both the telecommunications infrastructure and the power grid, which is essential for the BPL-LV project. MapInfo provides detailed data such as the location of each SFB in relation to lines and SS, distances between elements and SFB models, which is key information for assessing the effectiveness of BPL technology deployment according to the network topology.

B. *Grafana*

Grafana is a powerful and versatile tool for the visualization and analysis of data collected from equipment deployed in the network. Its main functionalities in the project include the creation of customized dashboards that represent in detail the performance of BPL equipment. Grafana enables connectivity and latency analysis through ping tests based on the Internet Control Message Protocol (ICMP), evaluating effective communication between devices. In addition, it monitors packet loss and response times (RTT - Round-Trip Time), critical indicators for determining network reliability and speed. The tool also allows configuring alerts and notifications for early detection of possible failures in the BPL-LV deployment, which facilitates fast and effective interventions. Data is collected and analysed at defined intervals, as in the case of this project, in the period from May 13 to 20, with a frequency of 5 minutes, ensuring consistent and detailed monitoring of network performance and the technology used.

C. *GridValue*

Corinex GridValue is an advanced grid management solution designed for monitoring and analysing data in the low-voltage grid. In the context of the project, GridValue provides near real-time monitoring of the availability and performance of deployed BPL devices, facilitating the operational optimization of the power grid. The software features detailed dashboards that provide information on device availability, allowing the active/inactive status of equipment to be tracked during specific periods, and enables the export of data such as transmit/receive rates, signal-to-noise ratio (SNR) and bit error rate (BER). In addition, GridValue includes a PHY rate analysis that evaluates the transmit and receive data rates for each SFB, essential for determining the efficiency of the BPL deployment. Visualization of the network topology is shown through a schematic representation of each SS configuration, including master devices, repeaters, data rates and active alarms, making it easy to quickly identify and resolve potential problems. Although GridValue allows viewing data individually, it was chosen to globally consolidate and analyse the information in a customized Excel sheet to gain a more comprehensive understanding of the network performance.

VI. Results Analysis Model

This section describes the analysis model used to evaluate the results obtained from the Grafana, GridValue and MapInfo tools. A structured approach was developed to represent and analyse the information of each secondary substation (SS) in a clear and visual way.

A. *Data Integration in Excel*

For each SS, an Excel workbook was created that organizes critical data such as network availability, latency, and transmission and reception speeds. Network availability was recorded through Grafana, measuring the percentage of packets lost during a week, with 5-minute intervals.

$$Availability\ (A_i) = 1 - \%\ Lost\ Packets \qquad (1)$$

This percentage was used to calculate availability, both averaged and weighted by the number of smart meters connected to each repeater.

$$Average\ Availability = \frac{1}{N} \cdot \sum_{i=1}^{N} A_i \qquad (2)$$

$$Weighted\ Average\ Availability = \frac{\sum_{i=1}^{N} w_i \cdot A_i}{\sum_{i=1}^{N} w_i} \qquad (3)$$

Latency was measured in milliseconds by ping analysis, and an average was calculated for each SS. Transmit and receive speeds were analyzed using GridValue data, evaluating each repeater individually.

B. *Graphic Representation in Excel*

Two main graphs were generated to analyze the network results for each SS:

- SS Complete Graph: this graph shows the average availability, weighted availability and average latency (RTT) throughout the week. It allows observing how availability and latency interact throughout the SS, identifying patterns and correlations.
- Individual Repeater Graph: For each repeater a specific graph is generated that presents the transmission and reception speeds along with the repeater availability. The availability data is grouped into one-hour periods, making it easy to visualize downtime or performance problems.

These graphs are designed to provide a detailed view of network and technology performance, both at the overall SS level and at the individual repeater level, facilitating deeper analysis and identifying areas for improvement in the BPL infrastructure.

C. *MapInfo Information*

Finally, an additional Excel sheet was included that collects relevant MapInfo data for each SFB, such as the line number, the previous upstream SFB to which it is connected, the distance between SFBs, the number of smart meters, the SFB model, and the IP and MAC addresses of the devices. This information is essential for the identification and analysis of the devices in the specific network environment.

VII. Repeater Location Algorithm

The deployment of BPL technology in the low-voltage grid presents a significant challenge due to the limited knowledge that utilities have of their own low-voltage grids. This lack of knowledge is due to the large number of connection points and the complexity of the network topology, which has not been studied or digitalized in depth.

A fundamental part of this project has focused on developing an algorithm to determine the minimum distances between repeaters, starting from the secondary substation, in order to optimize BPL deployment.

The process starts with the data provided by MapInfo, which includes the connections between SFBs and bifurcations (BF), and the distances between them.

Bifurcations are considered electrically equal points where repeaters cannot be placed.

In the first step, "Clusters" are identified, which are sets of SSs and/or SFBs linked to each other, directly or through bifurcations. For each low voltage line, arrays representing each cluster are created.

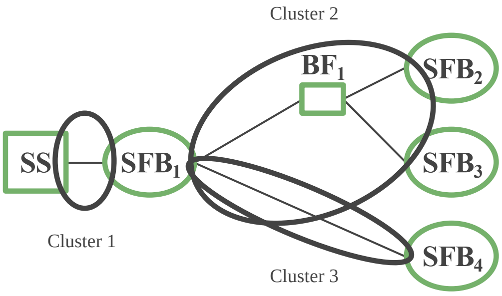

Figure 4. Example of Low Voltage Line with Identified Clusters.

Subsequently, each cluster is connected, starting with Cluster 1, which always contains the SS, identifying the anchor points to which the other elements are connected.

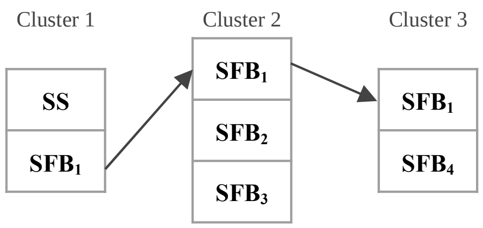

Figure 5. Pointer Designation.

In the third step, distances within each cluster are calculated by determining the distance between all SFBs.

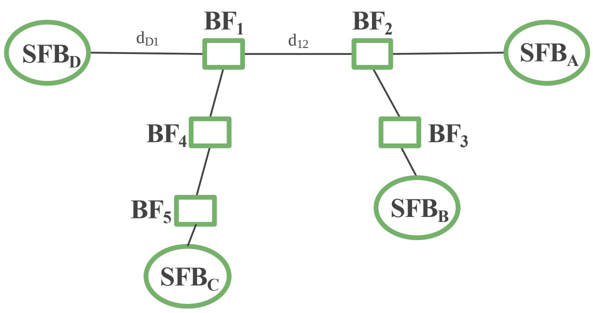

Figure 6. Cluster example.

Three groups of distances are identified: between SFBs, between SFBs and BFs, and between BFs. These distances are organized and simplified to find the central bifurcation that acts as the central reference point.

(a) S-S	(b) S-B	(c) B-B
	S_D-B_1= d_{D1}	B_1-B_2= d_{12}
	S_A-B_2= d_{A2}	B_1-B_4= d_{14}
	S_C-B_5= d_{C5}	B_1-B_3= d_{13}
	S_B-B_3= d_{B3}	B_4-B_5= d_{45}

Table 1. Initial Baseline Data.

Through an iterative process, the final distances between each SFB and the central bifurcation, and between the SFBs themselves, are obtained.

(a) S-S	(b) S-B	(c) B-B
d_{AB} = S_A-S_B = d_{12} + d_{A2} + d_{13}+ d_{B3}		
d_{AC} = S_A-S_C = d_{12} + d_{A2} + d_{45} + d_{C5}+d_{14}		
d_{AD} = S_A-S_D = d_{12} + d_{A2} + d_{D1}		
d_{BC} = S_B-S_C = d_{13}+ d_{B3} + d_{45} + d_{C5}+d_{14}		
d_{BD} = S_B-S_D = d_{13}+ d_{B3} + d_{D1}		
d_{CD} = S_C-S_D = d_{45} + d_{C5}+d_{14} + d_{D1}		

Table 2. Final distances result.

Then, these distances are placed in the form of a matrix to facilitate the selection of the minimum distances below. For the example just developed, the final matrix would be as follows:

$$\begin{pmatrix} - & C_A & C_B & C_C & C_D \\ C_A & X & d_{AB} & d_{AC} & d_{AD} \\ C_B & d_{AB} & X & d_{BC} & d_{BD} \\ C_C & d_{AC} & d_{BC} & X & d_{CD} \\ C_D & d_{AD} & d_{BD} & d_{CD} & X \end{pmatrix}$$

Finally, the minimum distances are selected starting from the SS. The next element within the cluster is chosen based on the shortest distance to the previous element, ensuring maximum coverage with the least number of repeaters. If an element is connected outside the cluster, the remaining elements are reanalysed

This algorithm, when integrated into MapInfo, provides an optimized solution for BPL repeater placement, ensuring maximum coverage and signal quality with the fewest number of repeaters required. It not only facilitates the efficient deployment of repeaters in the low-voltage network, but also contributes to improving knowledge about the network topology, overcoming current limitations and ensuring robust and reliable performance in the BPL network, especially in areas with complex and underexplored electrical infrastructure.

VIII. Results of the Research

This section provides a detailed analysis of the results obtained after the deployment of the hybrid BPL technology and PRIME v1.4 in 68 secondary substations. The main objective is to evaluate the effectiveness and performance of the implemented solution, identifying behavioral patterns and possible areas for improvement.

A. *Performance Overview*

The section presents a detailed analysis of the performance of the 68 secondary substations after the implementation of hybrid BPL technology and PRIME v1.4. To facilitate the understanding of the data, a table was generated that includes three key metrics for each substation: average availability, weighted average availability and average latency (ping), provided by Grafana. The table is visually organized with a conditional color format that helps to identify patterns and extremes quickly. This table is presented on the last page as Table 5.

The metrics shown include average availability, which reflects the percentage of time the substation was operational without packet loss during the period analyzed. Although values close to 100% could be interpreted as positive, the lack of a defined threshold implies that additional analysis is required before making definitive statements. Weighted average availability adjusts this metric according to the number of smart meters connected to each repeater, allowing the impact of the most critical repeaters on overall availability to be assessed. Latency, measured in milliseconds, indicates the time it takes for a data packet to make a round trip on the network. Lower latency generally suggests a faster network, although end-to-end latency measurements are not always relevant in this context.

The analysis of the table reveals significant variability among the substations in terms of availability and latency. Substations such as SS_{16}, SS_{39}, SS_{44} and SS_{68} show availability values close to 100%, which could indicate stable operation, although it cannot be categorically stated that these substations are operating "excellently" without a clear definition of the thresholds.

Figure 7. 100% Availability substations.

Substations such as SS_{25}, SS_{32} and SS_{56} also stand out, where there is a notable difference between average and weighted availability, suggesting that certain repeaters, especially those with a higher number of connected meters, have a more significant impact on the overall availability of the substation.

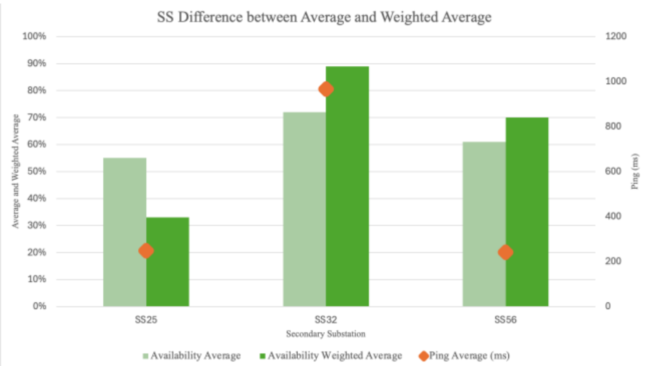

Figure 8. SS Difference between Average and Weighted Average Availability.

On the other hand, substations such as SS_{24} and SS_{54} show low availability but with low latency, which could suggest that these substations experience frequent outages, but when the network is operational, it works efficiently. It should be noted that in these cases, latency is likely to be more related to WAN connectivity, such as fibre or ADSL/FTTH, than to the number of BPL repeaters in the network.

B. Substation Selection for Detailed Analysis

Based on the results obtained with the Grafana data, it has been decided to perform an in-depth analysis of three substations to exemplify the different performance levels observed in the network. The substations chosen are SS_{20}, SS_{52}, and SS_{67}, each excelling in different categories of availability and latency, allowing a contrasting analysis of the operating conditions. In addition, an analysis of these substations with the values obtained from GridValue will be included to study their similitude.

To analyse substation performance in a detailed format, two categories were defined for each of the key metrics: availability and latency. It is essential to emphasize that these values have been established based on the data set available for this analysis and do not necessarily represent universal thresholds of either good or bad availability or latency. The following ranges are established for availability:

- High Availability (90% - 100%): Substations whose availability indicates almost continuous operation without significant interruptions.
- Medium Availability (70% - 89%): Substations with reasonable availability but experiencing some outages. This range suggests that the network is functional but may be facing occasional problems.
- Low Availability (0% - 69%): Substations with this availability indicate frequent interruptions or persistent problems in the network that affect its operability.

Latency categories were defined as follows, based on the distribution of values in this project:

- Low Latency (0 ms - 250 ms): Substations with fast response times, suggesting an efficient network in terms of data transmission speed.
- Medium Latency (251 ms - 800 ms): Substations with moderate response times. Although the network is functional, there may be some delay in data transmission.
- High Latency (801 ms - 2100 ms): Substations with slow response times, which could affect user experience and network efficiency.

The objective of this classification is to provide a clear and consistent framework for assessing SS performance, allowing for more detailed and comparative analysis in the following sections. This methodology ensures that the substations selected for analysis reflect a representative range of operating conditions observed in the network with the available data. The following table shows the corresponding availability and latency values for the selected SSs.

Secondary Substation	Availability Average	Availability Weighted Average	Ping Average (ms)
SS_{20}	100%	100%	64.39
SS_{52}	69%	65%	570.41
SS_{67}	26%	14%	43.38

Table 3. Secondary Substations to be studied.

In the availability and ping graphs provided, the average availability is plotted in blue, the weighted average availability is displayed in orange, and the latency in grey. In the data rate and availability graphs, the transmit rate is shown in orange, the receive rate is in blue, and the availability is in grey.

SS_{20} is a substation that is notable for its high availability and low latency, which makes it an ideal case for understanding the conditions that favour optimal performance. Both average and weighted availability remain consistently high, close to 100%, throughout the period analysed. This indicates that the network at this substation operates without significant interruptions, suggesting a robust and well-maintained infrastructure. It is especially notable that the weighted availability closely follows the average availability, indicating that there is no disproportionate impact on availability due to the number of smart meters connected to the different repeaters. This contributes to the overall stability of the substation, indicating an even distribution of load among the repeaters.

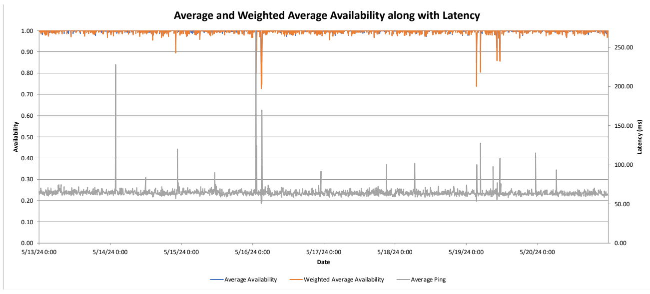

Figure 9. Average and Availability along with Latency SS_{20}.

The average latency in SS_{20} remains at low and stable levels, around 60 ms, with some isolated spikes that, although visually prominent, remain relatively low. This consistency in latency reinforces the perception of an efficient and fast performing network, without large variations in response times. The observed peaks, although isolated, could be due to brief moments of congestion or specific events in the network, but do not appear to significantly affect the overall availability of the substation.

In addition, the individual graphs for each repeater show that, although there is some variability in transmission and reception speeds, availability remains high in all cases, indicating that the infrastructure at SS_{20} can handle the load effectively, even at greater distances from the substation, as it can be observed in Figure 10 that shows one of the SFBs in the SS.

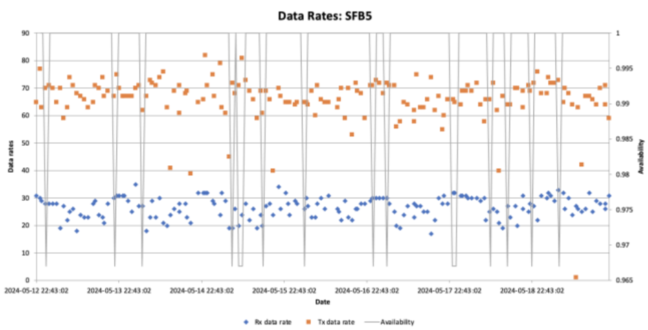

Figure 10. Data Rates SFB_5 SS_{20}.

SS_{52} represents an intermediate case with medium availability and latency, suggesting that the network at this substation faces stability and performance problems. The analysis reveals significant fluctuations in availability, with values varying between 50% and 90%, indicating that the network at SS_{52} is not operating optimally and suffers from instability. It is important to note that the weighted availability is generally lower than the average availability, suggesting that repeaters with more connected meters are experiencing lower performance in terms of availability. This difference suggests that the more heavily loaded areas are negatively affecting overall substation performance, which could be a key area for improvement.

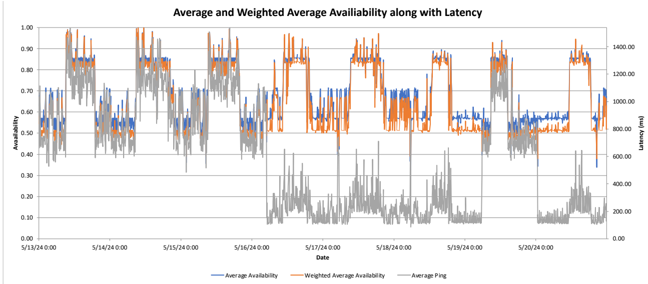

Figure 11. Average and Availability along with Latency SS_{52}.

The average latency on SS_{52} is high, with peaks exceeding 1000 ms on several occasions, suggesting that the network may be facing serious signal-to-noise ratio (SNR) problems due to the presence of noise in the low voltage network at certain times. From May 16 onwards, latency experiences a sudden and significant drop, remaining at much lower levels, around 200 ms, compared to previous days. However, this improvement is not long-lasting, since on May 19 latency increases abruptly again, reaching levels like those observed before May 16, only to decrease again on May 20. This behaviour could indicate the presence of an intermittent factor affecting network stability, such as fluctuations in noise levels, recurring technical problems or even external interference.

In addition, individual repeater graphs reveal unstable behaviour, with some repeaters, such as SFB_{11} and SFB_{12}, showing significant fluctuations in availability and low transmission and reception speeds, indicating serious infrastructure or signal quality problems.

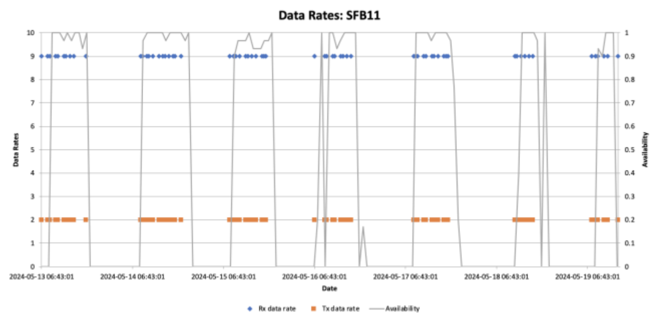

Figure 12. Data Rates SFB_{11} SS_{52}.

SS_{67} presents an interesting case due to its low availability, both average and weighted, despite having a relatively low latency. Availability at this substation remains at low levels throughout the period analysed, with a notable difference between average and weighted availability, the latter being consistently lower. This suggests that repeaters with more meters connected are facing greater problems, which negatively affects the overall availability of the substation. The observed variability in availability, with occasional peaks downwards, suggests the presence of intermittent outages that could be related to specific problems at specific times, such as overloading or occasional interference.

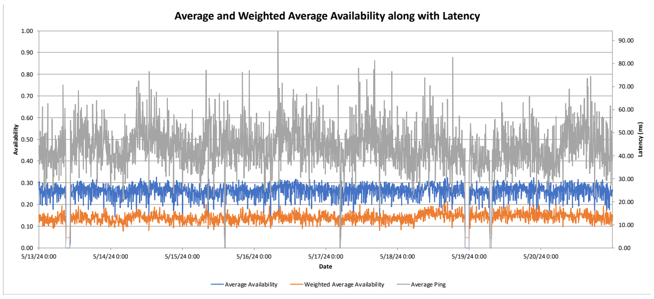

Figure 13. Average and Availability along with Latency SS_{67}.

The average latency at SS_{67}, although low compared to other substations, shows significant peaks at certain times, indicating variability in network performance. It is important to note that latency peaks do not always coincide with drops in availability, suggesting that the causes of high latency could be independent of interruptions in availability. These peaks could be due to temporary overloads or problems in the network infrastructure at specific times.

Individual repeater plots, such as SFB_1 and SFB_4, show stable but low transmit and receive rates, with availability varying considerably, indicating that distance to the substation and smart meter load are significantly affecting signal stability and overall substation performance. These results suggest that the infrastructure or management at SS_{67} requires improvement to achieve more stable and consistent performance.

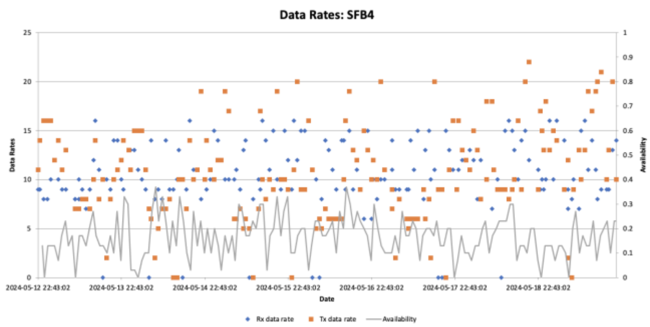

Figure 14. Data Rates SFB_4 SS_{67}.

C. *Availability Comparison between Grafana and GridValue*

In this section, a comparison is made between availability metrics obtained from two different tools, Grafana and GridValue, on three secondary substations: SS_8, SS_{10} and SS_{48}. The objective of this comparison is to assess the consistency and reliability of the data provided by these tools and, at the same time, to identify any discrepancies that may raise questions about the robustness of the measurements. It is important to note that Grafana and GridValue use different methodologies to collect these metrics, which may explain the variations observed in the results.

Grafana's availability is based on ICMP (Internet Control Message Protocol) data, using the percentage of packets lost as a key metric. This methodology, configured to collect data every 5 minutes, allows capturing short-term network outages with high accuracy, providing a granular view of network stability. On the other hand, GridValue presents two different types of availability data: a cumulative average that smooths out short-term variations and a more granular average that samples hourly, offering an intermediate perspective between the accuracy of Grafana and the smoothness of GridValue's cumulative average.

When comparing the data obtained from both tools in substations SS_8, SS_{10} and SS_{48}, some discrepancies are observed. For example, in SS_8, Grafana reports 84% availability, while GridValue shows a cumulative average of 95.42% and a granular average of 94.28%. These differences can be attributed to Grafana's ability to detect short outages that do not have a significant impact on GridValue's cumulative average. In contrast, in SS_{10}, the differences between the two tools are minimal, suggesting high data consistency and a stable network during the measurement period.

Secondary Substation	**Availabilit y Average (Grafana)**	**Availability Cumulative (GridValue)**	**Availability Average (GridValue)**
SS_8	84%	95.42%	94.28%
SS_{10}	99%	99.60%	99.20%
SS_{48}	85%	86.63%	89.22%

Table 4. Comparison between Grafana and GridValue for 3 SS.

The differences between Grafana and GridValue underline the importance of selecting the right tool for the type of analysis required. While Grafana is excellent for identifying transient problems and providing a detailed view of performance over short intervals, GridValue provides a more long-term view, which can be useful for assessing overall network stability. However, these differences also highlight the need for a clear understanding of the limitations and strengths of each tool to ensure accurate interpretation of the data.

In addition, it is important to consider that the choice of measurement tool can influence operational and network management decisions. For example, relying solely on GridValue's cumulative averages may miss intermittent problems that Grafana could detect. Therefore, in complex environments such as BPL networks, it can be beneficial to use both tools in a complementary manner to get a more complete picture of network performance and make informed decisions about network management and maintenance.

IX. Conclusions and Future Work

This section presents a summary of the main results obtained during the development of the project, evaluating the implementation and performance of hybrid BPL and PRIME v1.4 technology in low voltage grids. Through the analysis of data collected in 68 secondary substations, and using tools such as Grafana and GridValue, several objectives have been achieved, although challenges and areas requiring further research have also been identified. The conclusions underline the relevance of BPL technology in grid modernization, especially in low-voltage smart grids, while highlighting the need to refine measurement methodologies and broaden the scope of studies to ensure the robustness and applicability of results in wider contexts. In addition, suggestions for future work are outlined to consolidate the progress made and explore new opportunities to improve the implementation and evaluation of BPL technologies in low-voltage grids.

A. *Conclusions*

This project has evaluated in depth the implementation and performance of Corinex BPL and PRIME v1.4 (NB-PLC) hybrid technology in low voltage grids, leveraging tools such as Grafana and GridValue to monitor the behavior of 68 secondary substations. Throughout this process, several critical objectives have been achieved, although the project has also identified challenges and areas for improvement that deserve further attention in future research.

Broadband over Power Line technology is positioned as a key solution for enabling the Smart Grid in low-voltage networks, significantly enhancing the capabilities of narrowband PLC communications without adding cost to the current generation of smart meters. While it is possible that the next generation of smart meters, expected in 10 to 15 years, will be able to support BPL, current costs are unaffordable based on current regulatory regime. However, the continued development and deployment of BPL technology, as has been undertaken in this project, has the potential to stimulate the market and encourage the development of low-cost BPL solutions for the smart meters of the future. Other technologies, whether due to cost, availability or technical limitations (such as radio in massive subway environments), cannot guarantee ubiquitous deployment of broadband connectivity in low-voltage grids, making BPL a robust and cost-effective solution for managing the growing data demands in modern power grids.

Throughout the project, an Excel tool was developed that allowed the integration of data from Grafana, GridValue and MapInfo. This tool facilitated the visualization and dynamic analysis of availability and latency in the substations, allowing the identification of key patterns and specific problems in the network. While this tool represented a significant advance in performance analysis, the discrepancies observed in the data collected underscore the importance of employing multiple tools and approaches to obtain a more complete and accurate assessment of grid and Corinex technology performance.

One of the main objectives of the project was to analyse the performance of Corinex BPL technology in the selected substations. The results obtained showed that the technology has great potential to improve connectivity and monitoring capability in low voltage networks. However, a critical aspect identified was the inconsistency between the availability measurements and others reported by the two main tools used: Grafana and GridValue.

Grafana, with its 10-second sampling, showed greater sensitivity to short, transient outages in the grid, while GridValue offered cumulative measurements based on hourly values, which provides a more general and less detailed view. These methodological differences resulted in significant discrepancies, especially in certain substations, raising questions about which tool provides a more accurate and reliable view of grid and technology performance. This lack of consistency highlights the need for further exploration and refinement of measurement methodologies to establish more representative and reliable performance thresholds.

Although 68 secondary substations were included in the study, there exists the possibility that this sample may not be fully representative or meaningful to allow generalization of the results to other networks and environments. This limitation underscores the importance of conducting additional studies with larger and more varied samples to validate the findings and ensure that the results obtained are applicable to the entire low-voltage network.

The project has demonstrated that BPL technology has great potential to improve the connectivity and efficiency of low-voltage networks, especially in an environment where traditional narrowband solutions have limitations. However, the success of this technology is highly dependent on the ability to monitor and evaluate its performance in a consistent and reliable manner. The disparities observed between the tools used indicate that further analysis and adjustments in the methodologies are required to optimize the accuracy and reliability of the measurements.

In summary, the project has made significant progress in the implementation and evaluation of Corinex's BPL technology, meeting several of the initially stated objectives. However, the lack of consistency in the results obtained and the limitations in the representativeness of the sample suggest the need for further research and refinement of the methodologies used to ensure a more accurate and reliable evaluation of the performance of the technology in different environments.

B. Future Work

To give continuity to the work done in this project and address the challenges identified, the following next steps could be considered.

First, it is important to expand the sample size and geographic diversity of the secondary substations. Conducting additional studies with more substations located in different regions will improve the representativeness of the results, allowing validation of the current findings and ensuring consistency across diverse operating environments. This approach will also deepen the understanding of how local conditions and specific grid characteristics influence BPL performance. In addition, implementing cross-analysis using other measurement tools, beyond Grafana and GridValue, would be beneficial to verify data consistency and refine the methodologies employed.

Developing clear performance thresholds based on the data collected is crucial to accurately assess the success of BPL deployments. Establishing specific criteria for latency, availability and other key parameters will serve as a benchmark for future projects, facilitating early problem detection and technology optimization. In addition, refining and standardizing data collection and analysis methodologies will ensure consistency and comparability across future projects, creating a solid foundation for informed decision-making regarding BPL implementation.

It is important to investigate and test other BPL solutions available on the market to compare their performance with the Corinex technology used in this project. This evaluation will include not only the hardware and software, but also the monitoring, management and optimization capabilities offered by these alternatives. A comparative study will identify possible improvements or more suitable alternatives according to the specific needs of the network.

Improving the analytical tools currently in use, incorporating predictive analytics and modelling capabilities, will make it possible to anticipate potential problems and optimize technology performance more effectively. These improvements may include the development of more intuitive interfaces and advanced functionalities that facilitate data interpretation and decision making.

Ultimately, BPL technology stands out as a key solution for the modernization of power grids, offering significant benefits in terms of connectivity and efficiency. While lacking a standard designed for access low voltage grid, results so far are promising. Current state-of-the-art, with devices available to explore and understand better the low voltage grid, may lead to the selection and / or development of a new BPL solution addressing the specific challenges of this segment of the network, while paving the way for an eventual broadband PLC solution inside smart meters. The proposed next steps aim to consolidate the progress achieved, address the identified areas for improvement and explore new opportunities to optimize and expand the implementation of BPL in low voltage grids.

REFERENCES

[1] Sendin, A., Matanza, J., & Ferrús, R. (2021). Smart Grid Telecommunications: Fundamentals and Technologies in the 5G Era. John Wiley & Sons.

[2] Lopez, G., Matanza, J., De La Vega, D., Castro, M., Arrinda, A., Moreno, J. I., & Sendin, A. (2019). The role of power line communications in the smart grid revisited: Applications, challenges, and research initiatives. *IEEE access*, *7*, 117346-117368.

[3] Nessum. (2023, September 1). *Nessum technical overview — Key features that make Nessum one of the most advanced networking solutions*. Nessum. https://nessum.org/media/technology-blog/nessum-technical-overview

[4] Institute of Electrical and Electronics Engineers. (2018). *IEEE standard for medium frequency (less than 12 MHz) power line communications for smart grid applications* (IEEE Std 1901.1-2018). IEEE.

[5] González-Ramos, J., Uribe-Pérez, N., Sendin, A., Gil, D., de la Vega, D., Fernández, I., & Núñez, I. J. (2022). Upgrading the power grid functionalities with broadband power line communications: Basis, applications, current trends and challenges. *Sensors*, *22*(12), 4348.

[6] Sendin, A., Sanchez-Fornie, M. A., Berganza, I., Simon, J., & Urrutia, I. (2016). *Telecommunication networks for the smart grid*. Artech House.

[7] Hrasnica, H., Haidine, A., & Lehnert, R. (2005). *Broadband powerline communications: network design*. John Wiley & Sons.

[8] Kwon, B. W. (2009). Broadband over Power Lines (BPL): Developments and Policy Issues.

[9] Corinex. (2023, June 13). *E.ON chooses Corinex*. https://www.corinex.com/news/e-on-chooses-corinex

[10] Corinex. (n.d.). *Broadband over power lines*. Corinex. https://www.corinex.com/broadband-over-power-lines

[11] PRIME Alliance. (2021, September). *Towards a truly smart grid* (Summary). PRIME Alliance. https://www.prime-alliance.org/media/2021/09/TOWARDS-A-TRULY-SMART-GRID-Summary.pdf

X. Annex: Combined Study of the SS

Secondary Substation	Availability Average	Availability Weighted Average	Ping Average (ms)
SS1	100%	100%	1331.12
SS16	100%	100%	287.8
SS20	100%	100%	64.39
SS39	100%	100%	212.03
SS44	100%	100%	217.94
SS68	100%	100%	104.46
SS3	99%	99%	2079.98
SS10	99%	99%	275.6
SS11	99%	99%	1184.09
SS30	99%	100%	203.53
SS34	99%	98%	268.3
SS41	99%	99%	740.76
SS43	99%	99%	152.98
SS49	99%	99%	1074.06
SS53	99%	99%	1190.23
SS61	99%	99%	676.27
SS33	98%	99%	118.77
SS12	97%	98%	432.39
SS14	97%	97%	490.66
SS23	97%	98%	1141.68
SS42	97%	97%	459.29
SS45	97%	99%	636.4
SS51	97%	97%	233.23
SS66	97%	98%	745.5
SS59	96%	95%	594.14
SS13	94%	94%	658.42
SS46	94%	96%	577.86
SS63	94%	94%	277.01
SS47	93%	94%	234.99
SS6	91%	89%	211.08
SS55	90%	89%	1903.88
SS21	89%	91%	1355.75
SS27	87%	87%	182.1
SS28	86%	84%	917.94
SS31	85%	85%	401.12
SS48	85%	76%	144.24
SS8	84%	84%	433.48
SS37	84%	87%	483.95
SS22	83%	88%	1045.61
SS40	82%	83%	130.76
SS18	81%	88%	214.5
SS58	81%	84%	527.05
SS60	79%	81%	152.42
SS65	78%	82%	444.08
SS19	77%	86%	406.3
SS26	77%	79%	81.64
SS64	77%	87%	140.76
SS29	76%	75%	324.1
SS4	75%	76%	631.46
SS32	72%	89%	967.22
SS62	72%	54%	379.98
SS52	69%	65%	570.41
SS38	66%	66%	98.44
SS36	63%	57%	384.88
SS56	61%	70%	241.17
SS35	58%	50%	367.37
SS25	55%	33%	247.17
SS7	53%	45%	304.29
SS9	49%	27%	318.05
SS15	39%	40%	78.11
SS17	38%	26%	210.44
SS24	35%	28%	123.29
SS54	26%	30%	47.21
SS67	26%	14%	43.38
SS5	23%	43%	76.4
SS2	0%	0%	0
SS50	0%	0%	0
SS57	0%	0%	0

Table 5. Summary of SS results ordered by average availability.