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BROADBAND PLC OVER LOW VOLTAGE GRID: PILOT ROLL-OUT RESULTS ASSESSMENT AND FULL FORECASTING ROLL-OUT

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Madrid

Agosto de 2024

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BROADBAND PLC OVER LOW VOLTAGE GRID:

PILOT ROLL-OUT RESULTS ASSESSMENT AND FULL FORECASTING ROLL-OUT

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BANDA ANCHA PLC EN LA RED DE BAJA TENSIÓN: EVALUACIÓN DE LOS RESULTADOS DEL DESPLIEGUE PILOTO Y PREVISIÓN DE DESPLIEGUE COMPLETO

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RESUMEN DEL PROYECTO

Este proyecto evalúa la tecnología BPL híbrida y PRIME v1.4 en redes de baja tensión, destacando su impacto en la mejora de la eficiencia y la conectividad de la red, y proponiendo recomendaciones para optimizar su futuro despliegue.

Palabras clave: Broadband Power Line, Redes de Baja Tensión, Smart Grids, Recolección de Datos en Tiempo Real, PRIME v1.4.

1. Introducción

Este proyecto valora la implementación de la tecnología híbrida BPL y PRIME v1.4 en redes de baja tensión, analizando su rendimiento en 68 centros de transformación. Utilizando herramientas como Grafana y GridValue, se identificaron áreas que requieren una mayor investigación para optimizar la gestión y la estabilidad del rendimiento de la tecnología propuesta.

2. Definición del proyecto

El objetivo de este proyecto es estudiar y pronosticar la implantación de la tecnología Broadband Power Line (BPL) en redes de baja tensión. Buscando mejorar la eficiencia y capacidad de respuesta de estas redes, el proyecto aborda las limitaciones de la infraestructura existente basada en la tecnología PRIME v1.3 y NB-PLC.

Se propone una solución híbrida que extiende la tecnología BPL desde los centros de transformación hasta las cajas generales de protección, utilizando equipos Corinex y tecnología ITU G.hn. Además, se desarrolla un algoritmo para optimizar las distancias entre repetidores, mejorando el despliegue de BPL y abordando el limitado conocimiento de las empresas sobre sus redes de baja tensión.

3. Descripción del modelo

Este proyecto despliega una arquitectura híbrida que combina las tecnologías BPL y NB-PLC en redes de baja tensión, con el objetivo de mejorar la eficiencia y la gestionabilidad de las redes eléctricas. Desarrollada por i-DE, esta arquitectura extiende la tecnología BPL desde los centros de transformación (CT) hasta las cajas generales de protección (CGP) y las centralizaciones de contadores, utilizando la tecnología PRIME v1.4 desde los CT hasta los smart meters.

El modelo actual basado en PRIME v1.3, en uso desde 2010, tiene limitaciones en cuanto a la capacidad de transmisión de datos, lo que ha llevado a la necesidad de una solución más robusta. La nueva arquitectura híbrida introduce BPL para mejorar la capacidad de transmisión de datos, permitiendo velocidades en el rango de Mbps y optimizando la gestión de la red.

En la nueva configuración, la tecnología BPL se extiende de los CT a las CGP, utilizando la norma G.hn de la UIT con MIMO para mejorar la transmisión de datos. Desde las CGP, PRIME v1.4 gestiona la comunicación con los contadores inteligentes, reduciendo la latencia y mejorando la velocidad de respuesta de la red.

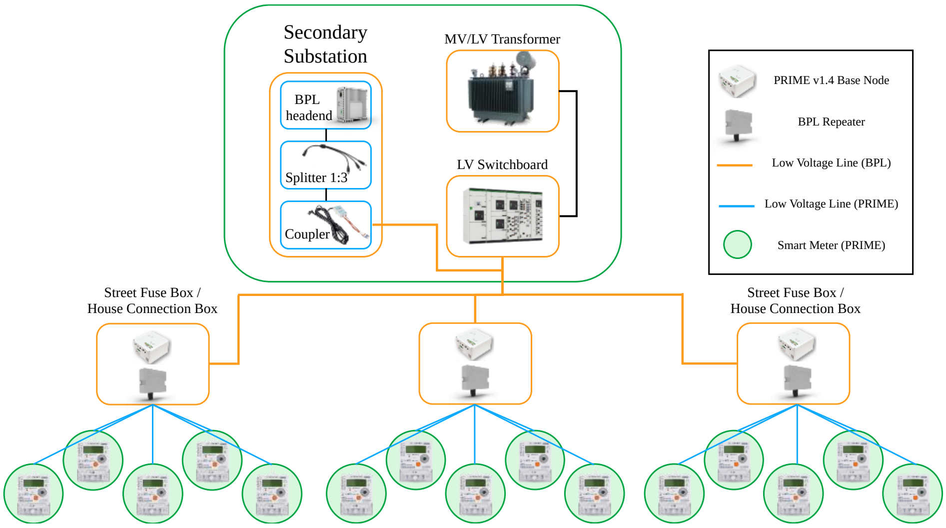

Ilustración 1. Solución Híbrida (BPL + PRIME v1.4).

La principal ventaja de esta arquitectura híbrida es su capacidad para manejar grandes volúmenes de datos con alta velocidad y baja latencia, lo que resulta esencial para la gestión en tiempo real y el cumplimiento de la normativa. Sin embargo, este enfoque también se enfrenta a importantes retos, como la coordinación de diversas tecnologías y la compatibilidad entre las infraestructuras existentes y las nuevas.

4. Resultados

El proyecto evaluó la implementación y el rendimiento de la tecnología BPL híbrida y PRIME v1.4 en 68 centros de transformación, con el objetivo de identificar patrones de comportamiento y áreas de mejora. Para ello, se utilizó una tabla que incluye tres métricas clave: disponibilidad media, disponibilidad media ponderada y latencia media (ping), extraídas de Grafana. Estas métricas permitieron una evaluación global del rendimiento del CT, revelando una variabilidad significativa tanto en la disponibilidad como en la latencia.

La disponibilidad media representa el porcentaje de tiempo que un CT estuvo operativa sin pérdida de paquetes, mientras que la disponibilidad media ponderada ajusta este valor en función del número de contadores inteligentes conectados a cada repetidor. La latencia mide el tiempo de ida y vuelta de un paquete de datos en la red, siendo un indicador clave de la velocidad de la red. En algunos CT se observaron diferencias notables entre la disponibilidad media y la ponderada, lo que sugiere que ciertas zonas con mayor carga de contadores se enfrentan a más problemas de conectividad.

Para un análisis más detallado, se seleccionaron tres CT representativos: CT_{20} (alta disponibilidad y baja latencia), CT_{52} (disponibilidad y latencia medias) y CT_{67} (baja disponibilidad y baja latencia). Estos CT permitieron explorar las condiciones específicas que influyen en su rendimiento, identificando patrones como la relación entre la distancia entre repetidores, la carga de los contadores y la estabilidad de la red.

Secondary Substation	Availability Average	Availability Weighted Average	Ping Average (ms)
SS20	100%	100%	64.39
SS52	69%	65%	570.41
SS67	26%	14%	43.38

Ilustración 2. Centros de Transformación a estudiar.

Además, se realizó una comparación entre las métricas de disponibilidad obtenidas con Grafana y GridValue para tres centros de transformación (CT_{8}, CT_{10} y CT_{48}). Grafana, con su intervalo de muestreo de 10 segundos, es muy sensible a los cortes transitorios, captando incluso las interrupciones más breves en la disponibilidad de la red. Por otro lado, GridValue proporciona una media acumulada basada en mediciones tomadas cada hora, lo que tiende a suavizar las fluctuaciones a corto plazo. Las discrepancias observadas entre las dos herramientas reflejan sus diferentes metodologías de captura de datos, lo que subraya la necesidad de un enfoque holístico que tenga en cuenta múltiples técnicas de supervisión y análisis para evaluar y optimizar plenamente el rendimiento de la tecnología.

Secondary Substation	Availability Average (Grafana)	Availability Cumulative (GridValue)	Availability Average (GridValue)
SS8	84%	95.42%	94.28%
SS10	99%	99.60%	99.20%
SS48	85%	86.63%	89.22%

Ilustración 3. Comparación entre Grafana y GridValue en 3 CTs..

En resumen, los resultados mostraron que, aunque la tecnología BPL tiene un gran potencial, la coherencia en el seguimiento y la evaluación es crucial para su éxito. Las diferencias entre Grafana y GridValue subrayan la importancia de utilizar múltiples enfoques para obtener una imagen completa y precisa del rendimiento de la tecnología.

5. Conclusiones

La BPL se perfila como una tecnología clave para la modernización de la red, al mejorar significativamente las capacidades de las comunicaciones de banda estrecha sin añadir costes a la actual generación de contadores inteligentes. Sin embargo, el éxito de su implantación depende en gran medida de la capacidad de supervisar y evaluar su rendimiento de forma coherente y fiable, así como de la alineación con los estándares de BPL.

Este proyecto ha evaluado la implementación y el rendimiento de la tecnología híbrida BPL y PRIME v1.4 en 68 subestaciones secundarias de la red de baja tensión. Una de las principales conclusiones fue la incoherencia en las mediciones de disponibilidad entre Grafana y GridValue, lo que puso de manifiesto la necesidad de perfeccionar las metodologías de evaluación y establecer umbrales de rendimiento más fiables. Grafana, con su mayor sensibilidad a las interrupciones cortas, proporcionó información detallada, mientras que GridValue ofreció una visión más acumulativa basada en datos horarios. Estos resultados destacan la importancia de adoptar un enfoque holístico que tenga en cuenta múltiples técnicas de monitorización para obtener una comprensión exhaustiva del rendimiento de la tecnología.

Para futuros trabajos, se recomienda ampliar la muestra de subestaciones estudiadas y validar los resultados utilizando herramientas adicionales para garantizar la representatividad y coherencia de los datos. Además, es esencial desarrollar criterios de evaluación claros para definir umbrales de rendimiento, explorar soluciones alternativas de BPL y evaluar su alineación con diferentes estándares de BPL. La mejora continua de las herramientas analíticas, incluida la incorporación de capacidades predictivas y de modelización, también será crucial para anticipar y abordar posibles problemas.

BROADBAND PLC OVER LOW VOLTAGE GRID: PILOT ROLL-OUT RESULTS ASSESSMENT AND FULL FORECASTING ROLL-OUT

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Collaborating Entity: IBERDROLA ESPAÑA, S.A.U.

ABSTRACT

This project assesses hybrid BPL technology and PRIME v1.4 in low-voltage networks, highlighting its impact on improving network efficiency and connectivity, and proposing recommendations to optimize its future deployment.

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

1. INTRODUCTION

This project evaluates the implementation of hybrid BPL technology and PRIME v1.4 in low voltage networks, analyzing their performance in 68 substations. Using tools such as Grafana and GridValue, areas were identified that require further investigation to optimize the management and stability of the proposed technology's performance.

2. PROJECT DEFINITION

The objective of this project is to evaluate and forecast the implementation of Broadband Power Line (BPL) technology in low voltage networks. Seeking to improve the efficiency and responsiveness of these networks, the project addresses the limitations of the existing infrastructure based on PRIME v1.3 and NB-PLC technology.

A hybrid solution is proposed that extends BPL technology from secondary substations to meter panels, using Corinex equipment and ITU G.hn technology. In addition, an algorithm is developed to optimize the distances between repeaters, improving the deployment of BPL and addressing the limited knowledge of companies about their low voltage networks.

3. MODEL DESCRIPTION

This project deploys a hybrid architecture that combines BPL and NB-PLC technologies in low-voltage grids, with the objective of improving the efficiency and manageability of power grids. Developed by i-DE, this architecture extends BPL technology from secondary substations (SS) to street fuse boxes (SFB) house connection boxes (HCB), using PRIME v1.4 technology from SFB to smart meters (SM).

The current PRIME v1.3-based model, in use since 2010, has limitations in terms of data transmission capacity, which has led to the need for a more robust solution. The new hybrid architecture introduces BPL to improve data transmission capacity, enabling speeds in the Mbps range and optimizing network management.

In the new configuration, BPL technology extends from SSs to SFBs, using the ITU G.hn standard with MIMO to improve data transmission. From the SFBs, PRIME v1.4 handles communication with the smart meters, reducing latency and improving network response speed.

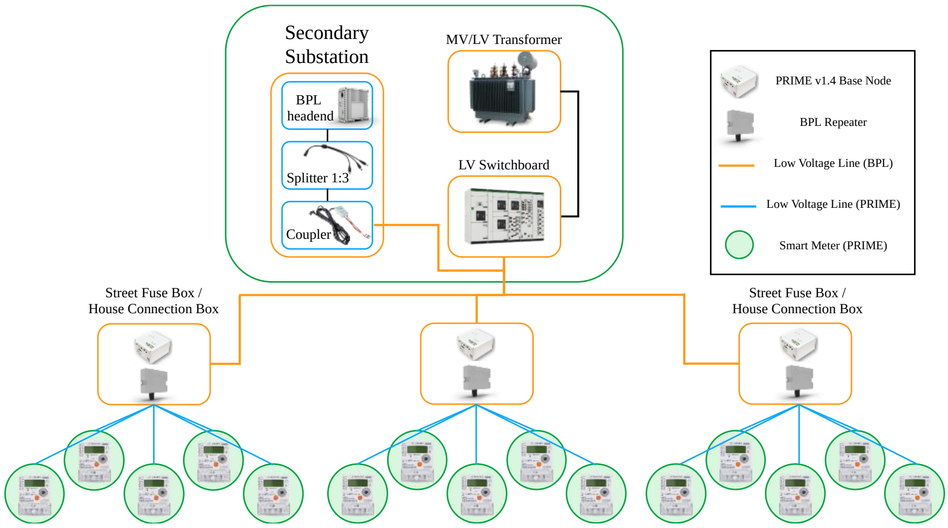

Illustration 1. Hybrid Solution (BPL + PRIME v1.4).

The main advantage of this hybrid architecture is its ability to handle large volumes of data with high speed and low latency, which is essential for real-time management and regulatory compliance. However, this approach also faces significant challenges, such as the coordination of diverse technologies and compatibility between existing and new infrastructures.

4. RESULTS

The project evaluated the implementation and performance of hybrid BPL technology and PRIME v1.4 in 68 secondary substations, with the objective of identifying behavioural patterns and areas for improvement. To this end, a table was used that includes three key metrics: average availability, weighted average availability and average latency (ping), extracted from Grafana. These metrics allowed an overall assessment of substation performance, revealing significant variability in both availability and latency.

Average availability represents the percentage of time a substation was operational without packet loss, while weighted average availability adjusts this value according to the number of smart meters connected to each repeater. Latency measures the round-trip time of a data packet in the network, being a key indicator of network speed. Notable differences between average and weighted availability were observed in some substations, suggesting that certain areas with higher meter load face more connectivity problems.

For a more detailed analysis, three representative substations were selected: SS_{20} (high availability and low latency), SS_{52} (medium availability and latency) and SS_{67} (low availability and low latency). These substations allowed to explore the specific conditions that influence their performance, identifying patterns such as the relationship between the distance between repeaters, meter load and network stability.

Secondary Substation	Availability Average	Availability Weighted Average	Ping Average (ms)
SS20	100%	100%	64.39
SS52	69%	65%	570.41
SS67	26%	14%	43.38

Illustration 2. Secondary Substations to be studied.

In addition, a comparison was made between availability metrics obtained with Grafana and GridValue for three substations (SS_8, SS_{10} and SS_{48}). Grafana, with its 10-second sampling interval, is very sensitive to transient outages, capturing even the shortest interruptions in grid availability. On the other hand, GridValue provides a cumulative average based on measurements taken every hour, which tends to smooth out short-term fluctuations. The discrepancies observed between the two tools reflect their different data capture methodologies, underscoring the need for a holistic approach that considers multiple monitoring and analysis techniques to fully evaluate and optimize technology performance.

Secondary Substation	Availability Average (Grafana)	Availability Cumulative (GridValue)	Availability Average (GridValue)
SS8	84%	95.42%	94.28%
SS10	99%	99.60%	99.20%
SS48	85%	86.63%	89.22%

Illustration 3. Comparison between Grafana and GridValue for 3 SS.

In summary, the results showed that although BPL technology has great potential, consistency in monitoring and evaluation is crucial to its success. The differences between Grafana and GridValue underscore the importance of using multiple approaches to get a complete and accurate picture of the technology's performance.

5. CONCLUSIONS

BPL stands as a key technology for grid modernization, significantly enhancing the capabilities of narrowband communications without adding cost to the current generation of smart meters. However, the success of its deployment depends heavily on the ability to consistently and reliably monitor and evaluate its performance, as well as alignment with BPL standards.

This project has evaluated the implementation and performance of hybrid BPL and PRIME v1.4 technology in 68 secondary substations of the low voltage grid. One of the main findings was inconsistency in availability measurements between Grafana and GridValue, highlighting the need to refine evaluation methodologies and establish more reliable performance thresholds. Grafana, with its greater sensitivity to short outages, provided detailed information, while GridValue offered a more cumulative view based on hourly data. These results highlight the importance of taking a holistic approach that considers multiple monitoring techniques to gain a comprehensive understanding of technology performance.

For future work, it is recommended to expand the sample of substations studied and validate the results using additional tools to ensure the representativeness and consistency of the data. In addition, it is essential to develop clear evaluation criteria to define performance thresholds, explore alternative BPL solutions, and evaluate their alignment with different BPL standards. Continuous improvement of analytical tools, including the incorporation of predictive and modelling capabilities, will also be crucial to anticipate and address potential challenges.

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Chapter 1. INTRODUCTION

Chapter 1 will address several key points that underpin and structure the project. Starting with the global and specific context of the energy sector, this section will highlight the urgent need for decarbonisation and the adoption of advanced digital technologies. Then, the motivation of the project will be presented, focusing on overcoming the current limitations of NB-PLC technology by implementing BPL to improve the operational efficiency and reliability of the power grid, through the use of advanced broadband communications.

The specific objectives of the project will then be outlined, including the analysis of the performance of secondary substations equipped with BPL and the development of optimised methodologies and tools for future deployments. The work methodology will describe the approaches and processes to be followed to achieve these objectives, while the resources section will detail the means and materials required. Finally, the structure of the thesis will be presented, providing an overview of how the content of the document will be organized and developed.

1.1 CONTEXT

The global energy sector stands at a critical inflection point marked by the urgent need for decarbonization and the adoption of advanced digital technologies. This transformation is driven by multiple factors, including the fight against climate change, growing energy demand and technological innovation.

A key driver of this transformation is the transition to renewable energy sources. By 2024, the share of renewables in electricity generation is projected to increase significantly, reaching between 45% and 50% by 2030, and between 65% and 85% by 2050 [1]. This shift is being driven by significant investments in clean energy, supported by policies and regulations, such as the Inflation Reduction Act (IRA) and the Infrastructure Investment and

Jobs Act (IIJA) in the US, which have raised billions of dollars for renewable infrastructure development [2].

In addition to investment in renewables, the electrification of several sectors is another key factor. The adoption of electric vehicles (EVs) is increasing rapidly. In 2023, EV sales accounted for 9% of total car sales in the first three quarters of the year and are expected to reach the milestone of one million cars sold annually [2]. This growth in electricity demand requires greater storage capacity and more flexible grid management.

In Spain, i-DE, Iberdrola's distribution subsidiary, has been a pioneer in implementing innovations in the electricity system. With the STAR project, i-DE transformed its distribution network by installing 11 million smart meters and modernising 99,000 substations [3], including upgrading the telecommunications infrastructure for access to secondary substations to broadband. This project, which is part of the Iberdrola initiative, has improved operational efficiency and service quality.

The medium-term objectives of i-DE include encouraging the use of electric vehicles and improving the monitoring and control of the grid to provide a high-quality service in real time. In addition, i-DE aims to become a Distribution System Operator (DSO), which involves managing bi-directional flows of electricity and promoting the active participation of 'prosumers' (consumers who also produce energy) [3].

To achieve these goals, a robust and efficient communication infrastructure is essential. Hence, this is where Power Line Communications (PLC) technology comes into play. PLC enables data transmission over existing power lines, facilitating fast and reliable communication between the various components of the grid, such as distribution substations and smart meters.

The current project, a pilot roll-out, proposes the deployment of Broadband Power Line Communication (BPL) technology in the low voltage network. This technology will enable faster and more effective communication, enabling real-time functionalities that are necessary for advanced network management. The integration of BPL will not only improve efficiency and quality of service, but will also increase the connectivity of consumers, providing real-time data on their consumption patterns.

It is important to highlight the great importance of introducing this BPL technology in low voltage, which allows "professional" telecommunications to be achieved, which with previous technology reached secondary substations, and with this project can penetrate increasingly closer to the end point of the network, in this case, to the street was boxes. From a telecommunications point of view, just as the STAR project brought these "professional" telecommunications to all secondary substations, this project drives it further down, to the edge of the grid, which is the low voltage.

Real-time data collection in the low-voltage grid is a critical need for utilities seeking to improve the operational efficiency, reliability and quality of service of their power grids. Currently, Narrowband PLC (NB-PLC) technology is widely used for smart metering and other functions in the low voltage grid, but it has significant limitations, such as data updates every 15 minutes and the complexity of managing high volumes of data, which does not allow for effective real-time monitoring.

The main driver for this project relates to the need to overcome these limitations by implementing BPL technology in the low-voltage grid. BPL offers much higher data transmission rates and significantly lower latency, enabling real-time data collection and faster response to events in the network. In addition, the use of BPL in the low-voltage grid paves the way for telecontrol, which is currently only available in high and medium voltage. This allows low voltage ringed structures to be operated in the secondary substations of the utility's decision.

Specifically, this document analyses the results of the BPL deployment and assesses its status. This analysis will help determine the effectiveness of the deployed technology and its ability to meet the project's objectives, facilitating informed decision-making for future larger-scale deployments or a change to another type of technology.

Combining PLC technology with Smart Grids and i-DE's decarbonization goals represents a fundamental step towards the modernization of the energy sector. This integration not only aligns sustainability and efficiency goals, but also enhances the advanced management and operational capabilities of the electricity infrastructure, preparing the way for a greener and more connected energy sector.

1.2 MOTIVATION

Globally, electricity grids are rapidly evolving towards smarter and more efficient systems. This change is driven by the need to improve the operation, reliability and quality of service of power grids, as well as by the integration of renewable energies and the digitalization. In this context, the implementation of advanced communication technologies, such as BPL, presents itself as a key solution.

The low-voltage power grid mainly uses NB-PLC technology for smart metering and other operational functions. However, this technology has significant limitations, especially in terms of real-time monitoring capability. Data collected by smart meters is updated every 15 minutes and cannot be received in real time, which impedes effective monitoring and response to events in the grid. This limitation is a significant constraint to the current and future needs of electricity distribution networks.

The goal of electricity distribution companies, such as i-DE, is to evolve from DNO to DSO. This transition involves not only managing traditional electricity infrastructure, but also integrating renewable energy sources, distributed energy resources, electric vehicles and the ability to collect and analyse real-time data. Digitalization is fundamental to this transformation, and BPL technology in the low-voltage grid seems a viable option for achieving this.

BPL technology enables the collection and analysis of large volumes of data in real time, which optimizes the operation of power grids. This capability facilitates the rapid identification and resolution of faults, demand management and optimization of power distribution [3]. Implementing BPL improves outage response capability, enabling faster and more efficient problem detection and resolution, minimizing downtime and ensuring a consistent and reliable power supply. In addition, this ability is essential to effectively integrate renewable energy sources, such as solar and wind, which are intermittent and require dynamic management to maintain the balance between generation and demand [3].

The real-time monitoring capabilities provided by BPL help utilities comply with regulations that require greater transparency in the operation of electricity grids. This includes providing accurate, real-time data on grid status and performance [4]. The ability to provide real-time information on energy consumption allows consumers to make more informed decisions and better manage their energy use, resulting in cost savings and increased customer satisfaction [3].

Crucially, unlike other communication technologies, BPL is particularly suited to the low-voltage grid due to its ability to provide broadband connectivity using existing electrical infrastructure. BPL operates in a higher frequency range than narrowband PLC, enabling higher data transfer rates, essential for Smart Grid applications that require real-time data transmission. In addition, BPL's robustness to interference and ability to adapt to varying channel conditions make it particularly effective in LV environments where network topology is complex, and noise conditions are high [22].

Many other technologies, such as wireless solutions, present significant difficulties in massive underground environments due to signal attenuation and coverage limitations. These technologies can also be expensive to deploy on a large scale in the LV [22]. In contrast, BPL leverages already installed power lines, which significantly reduces deployment costs and facilitates large-scale adoption. Therefore, BPL is not only positioned as an efficient solution for data transmission in the LV grid, but also as the most practical and viable option in many cases to achieve a ubiquitous Smart Grid in this power grid layer.

This project is motivated by the need to overcome the current limitations of NB-PLC technology and take advantage of the benefits of BPL to improve the operational efficiency, reliability and quality of service of electricity grids, while facilitating the integration of renewable energy and ensuring regulatory compliance.

It is important to note that BPL technology cannot be proven on a large scale without end products that can be permanently installed in the field. The development of such products requires significant investment, which is only justified if there is a market demand for the technology and if the technology has proven to solve the problems it faces. This analysis is crucial to test Corinex's specific BPL technology to determine whether it meets the identified needs, as well as to identify where it is not working properly and to address these challenges with other solutions. Although several BPL technologies exist today for the network, none have been developed specifically for BT's access network. Corinex has implemented an adapted version from the standard that allows for a better understanding of the network and deployment of equipment. It is as important to identify where it works well as where it does not, as this is not a failure, but a necessary step to further develop and refine the technology.

To achieve all the above, i-DE needs to analyse the BPL technology already deployed in the low voltage network, provided by Corinex. This will determine whether this technology meets the above needs, as well as other possible locations where the technology will work properly. Alternatively, if this technology offered by Corinex does not perform its expected functionalities correctly, there is the possibility that a different BPL technology other than Corinex's could be employed.

1.3 PROJECT OBJECTIVES

This project aims to address the current limitations in real-time data collection, as well as the management of large volumes of data, in the low-voltage grid by implementing BPL technology. To achieve this, several specific objectives have been established to guide the development and implementation of the project.

The first objective is to perform a detailed analysis of the real-time performance of secondary substations (SS) already deployed with BPL technology. This involves collecting data for a minimum of one week, the results of which will be analysed and documented, in order to determine the improvements to be implemented in each SS. Thus, a summary of the actions taken to optimize their operation and efficiency is provided.

Another objective of the project is to develop the methodologies and tools necessary to carry out the analyses in an efficient and optimized manner. This includes the development of reproducible and scalable processes for future BPL deployments. A methodology will also be developed for the topological analysis of SS, assessing their relationship with BPL signal propagation. This analysis will allow the identification of the most suitable SS for BPL deployment and improve network planning. It is also essential to develop tools that facilitate topological analysis in an effective manner, allowing the categorization of SS according to their suitability for BPL deployment. These tools will optimize the deployment process and ensure a successful implementation.

With these objectives, the project aims not only to improve the efficiency and reliability of the power grid using BPL technology, but also to establish a solid basis for future implementations and optimizations in the low voltage grid.

In summary, the project is designed to address the current limitations in the collection and handling of large volumes of real-time data in the low voltage grid by implementing BPL technology. All this in conjunction with the BPL technology implemented by i-DE and provided by Corinex. To achieve all these objectives, it is necessary to perform a technical analysis of the results, and especially of those secondary substations where the technology does not work properly. To facilitate this process, a joint and correlated collection of all available data from these locations where the expected results are not being achieved is necessary, in order to deduce the potential reasons for this performance.

1.4 WORK METHODOLOGY

The execution of the project follows a structured methodology to ensure the comprehensive collection and analysis of relevant data necessary for the achievement of the project. Each of the key stages of the process is detailed below.

The initial phase consisted of an extensive literature review to become familiar with the subject of powerline communications and its applications in low voltage networks. This review covered academic articles, technical reports and relevant standards, serving to provide the necessary background information. In parallel, several meetings were held with the industrial advisor to receive guidance and clarify concerns about the project approach and expectations.

After completing the research phase, I actively acquired expertise in various tools and software essential to the project. This included gaining knowledge in the geographic information system (GIS) MapInfo, as well as in the programs GridValue and Grafana. MapInfo was utilised to obtain topological data from the secondary substations (SS), while Grafana and GridValue were essential for collecting and analysing performance data of Corinex BPL at low voltage.

The next step involved collecting specific information from each of the 70 secondary substations with Corinex BPL technology deployed. This data was gathered from various tools, each operating in different environments and providing information in diverse formats and levels of granularity. This process included the following tasks:

- Topological data obtained through MapInfo, including the different lines that comprise the corresponding secondary substation, the layout, connection and distance between different Street Fuse Boxes (SFB) and the secondary substation, as well as the number of customers of each SFB.
- Collection of availability data using Grafana, obtaining the percentage of packets lost in the entire SS over one week, with data recorded every 5 minutes. This approach

represents a compromise between de maximum level of detail available (ping every 10 seconds), and the need for data that can be meaningfully analysed over week-long periods. Additionally, a ping study of the SS was conducted for one week, with data recorded at 5-minute intervals.

- Compilation of data speed rates and voltages of each phase using GridValue, for each SFB of the SS analysed.

After data collection, an Excel file was developed to integrate relevant information from MapInfo, Grafana and GridValue. The choice of Excel was driven by its flexibility in automating data collection and processing, as well as its capability to serve as a graphical user interface (GUI) for dynamic data visualization. This Excel file was designed to display data collected over a week, with the added functionality of allowing users to focus on specific days without the need to manually adjust axes or formatting. The interface was automated using buttons, enabling dynamic visualization and easy navigation through the data. The integrated Excel file includes:

- A graph showing the average SS availability both weighted by the number of smart meters of each SFB and unweighted, alongside the average SS ping.
- Individual graphs for each SFB representing the reception and transmission data rates, as well as their availability represented hourly.

Once all the information was organized and visualized, an exhaustive analysis of the data was performed. This analysis allowed determining the effectiveness of Corinex's BPL technology in each SS, evaluating whether it met performance and availability expectations. Finally, specific conclusions were drawn for each transformation centre, providing a solid basis for the evaluation of the pilot implementation and the planning of future deployments. The following diagram is included to facilitate the visualization of the methodology used.

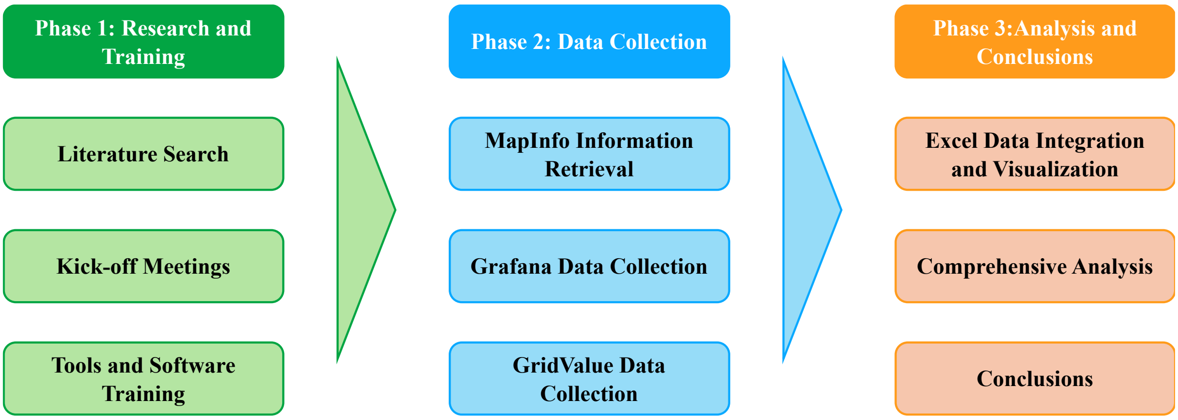


Figure 1. Diagram of the methodology.

1.5 RESOURCES

The project involved the use of various documentary resources as well as technological and software tools that facilitated the research, data collection and analysis.

First, documentary resources were used for the literary study, in order to obtain an in-depth knowledge of BPL technology. Multiple IEEE documents were consulted as a key source of technical and scientific information in the field of telecommunications and electrical networks. In addition, the previous year's thesis by Ayala Bernaola, L. (2023) entitled "Broadband PLC over Low Voltage Deployment: Planning Tool Development", available at the Comillas Repository, was used, since this project is a direct continuation of that work. News and publications on the use of Corinex BPL technology by other companies were also reviewed, providing a practical and up to date perspective on its implementation and effectiveness in different contexts.

Furthermore, several technological tools were used, such as MapInfo, GridValue and Grafana, which are briefly described in this section, but will be developed further in Section 4 of the project.

- MapInfo (GIS): MapInfo Professional is a geographic information system used for the collection, management and analysis of spatial data. This software allows data to be organized into visualizations using 3D maps, facilitating the analysis of the low voltage network in both electrical and telecommunications terms. At Iberdrola, MapInfo is used to graphically represent all the company's telecommunications assets and to visualize the medium and low voltage electrical network, which is crucial for obtaining a comprehensive view of the infrastructure and its condition.
- Grafana: Grafana is a software used for the visualisation of data collected from deployed equipment. It allows the customisation of dashboards that represent the performance of this equipment, transforming data measured in the field into meaningful graphs. In this project, Grafana was customised to display the results of a ping analysis between different transformation centres, helping to assess the connectivity and latency of the newly deployed network [3].
- GridValue: Corinex GridValue is a grid management software that aggregates and analyses data, providing sensing capabilities for the low voltage grid. This tool is essential for managing integrated BPL product deployments, enabling utilities to deliver smart grid applications and distributed energy resource services. GridValue can manage up to 5 million nodes, supports 2 million messages per minute and 10,000 configuration requests in parallel, and is based on a microservices architecture with a versatile and customisable user interface. The software includes integrated GIS and other visualisation tools that provide a clear and detailed view of the real-time status of the network. This allows network operators to quickly identify problems and make informed decisions for resolution [19].

Finally, Microsoft Excel was used to analyse the collected data, providing a powerful tool to organise, visualise and evaluate the information. Excel allowed the integration of data from MapInfo, Grafana and GridValue, which facilitated the creation of customized graphs and the calculation of relevant statistics. For example, Excel was employed to generate graphs that showed weekly trends in availability and latency across the SS, with flexibility to drill down into specific days through automated controls. This approach was key for evaluating and validating the performance of BPL technology in the secondary substations, allowing for detailed analysis without the need for manual adjustments of axes or formats.

1.6 THESIS STRUCTURE

This thesis is organized in seven chapters that cover from the theoretical and technological context to the analysis of results and final conclusions. The content of each of these chapters is briefly described below.

Chapter 1, as has been noted, introduces the project, providing the context, motivation and specific objectives to be achieved. In addition, it describes the work methodology employed, and the resources used throughout the development of the project.

Chapter 2 focuses on the description of the technologies relevant to this project. It explores traditional and new Smart Grid applications, the different power line communication (PLC) technologies in their ultra-narrowband, narrowband and wideband variants, and presents a description of the power distribution system, with a particular focus on secondary substations and other key components relevant to the project. The Geographic Information System (GIS), which plays an important role in the planning and management of low voltage networks, is also introduced.

Chapter 3 provides a state of the art contextualizing the use of PLC technology at different voltage levels, with a special emphasis on low voltage networks. The fundamentals of BPL are explored, including international standards such as IEEE 1901 and technologies such as Nessum and HomePlug. The technological, socioeconomic and regulatory challenges facing the implementation of BPL are also addressed, and case studies of similar projects using this technology are presented.

Chapter 4 describes in detail the model developed in this project. It starts with the definition and justification of the project, followed by an exhaustive description of the hybrid architecture model implemented, which combines BPL technology and PRIME v1.4. The technologies and tools used, such as MapInfo, Grafana and GridValue, are also discussed, and the algorithm developed for the optimal location of repeaters in the secondary substations is presented.

Chapter 5 presents the results of the research, starting with an overview of the performance of the secondary substations evaluated. The performance of selected substations, categorized according to their availability and latency, is analysed in detail, and a comparison is made between the availability measurements obtained with Grafana and GridValue, highlighting the discrepancies observed and the possible causes of these differences.

Finally, Chapter 6 concludes the thesis, summarizing the achievements, the contributions made and the areas that require further research in the future. Suggestions for future work that can extend and validate the findings of this project are also proposed.

Chapter 7 compiles the bibliographical references used throughout the research, providing a solid theoretical support framework.

Annex I presents a detailed study of the secondary substations evaluated in the project. A summary table is included with the average availability, weighted availability and average latency results for the 68 substations with hybrid BPL technology and PRIME v1.4 deployed, using Grafana as the data collector software. This information is organized in two additional formats that allow for better visualization and analysis of patterns among the parameters.

Annex II provides the data rate and availability graphs for a particular secondary substation (SS67) that were not shown in Section 5.2.3.

Annex III discusses how the project aligns with several Sustainable Development Goals (SDGs) established by the UN. In particular, it highlights the SDGs related to affordable and clean energy (SDG 7), industry, innovation and infrastructure (SDG 9), sustainable cities and communities (SDG 11) and climate action (SDG 13).

Chapter 2. DESCRIPTION OF THE TECHNOLOGIES

In the context of the evolution of power grids, Smart Grids have emerged as an innovative solution to improve energy efficiency and management. This chapter provides a detailed description of the technologies involved in these grids, covering both their traditional applications and the innovations that are transforming the energy sector.

Smart Grids integrate advanced communication and control technologies to optimise electricity distribution and consumption. This chapter starts with an overview of traditional smart grid applications, such as remote control and metering, and moves on to new applications including the integration of renewable energies and the development advanced metering infrastructure.

A particular focus is devoted to Power Line Communication (PLC) technologies, essential for data transmission over the existing electrical infrastructure. The different types of PLCs are explored: UNB-PLC (Ultra Narrowband PLC), NB-PLC (Narrowband PLC) and BPL (Broadband PLC), detailing the standards and protocols governing each of these systems.

The chapter also analyses the distribution section of the power grid, highlighting the main components such as primary and secondary substations, and medium- and low-voltage lines. These elements are fundamental to the operation of smart grids, as they support both the power and data transmission necessary for their efficient operation.

2.1 SMART GRIDS

Smart grids represent an evolution in the way electricity is generated, distributed and consumed. Unlike traditional electricity grids, Smart Grids incorporate advanced information and communication technologies (ICT) to improve the efficiency, reliability and security of electricity supply [5]. The main goal of Smart Grids is the optimization of the power system, to minimise losses and improve the reliability of supply.

Energy demand is constantly growing and, therefore, the need to integrate renewable energy sources is becoming essential. These Smart Grids allow for better demand management and more effective integration of distributed energy sources, such as solar and wind [5]. In addition, they enable real-time monitoring and automated decision-making, resulting in a more robust and adaptive operation of the power grid in the event of failures or fluctuations in demand [6].

The development of Smart Grids also has a significant impact on the end-user, transforming passive consumers into active participants in the energy system [5]. Consumers can better manage their consumption, generate their own energy and contribute to balancing the grid through technologies such as smart meters and energy storage systems [6].

This section will explore in detail the traditional applications of Smart Grids, which have been fundamental to the basic operation of electricity grids, and the new applications that are transforming the energy sector.

2.1.1 Traditional Smart Grids Applications

Traditional Smart Grid applications have been primarily focused on monitoring and controlling the existing electrical infrastructure. These applications include distribution and transmission management systems, smart metering and demand-side management programmes, all designed to optimise grid operation and reduce energy losses [6].

2.1.1.1 Remote Control

Traditional Smart Grid applications focus on the supervision and control of electricity distribution and transmission. Supervisory Control and Data Acquisition (SCADA) systems allow real-time monitoring of the status of transformers, substations and transmission lines [6].

SCADA systems collect data from sensors distributed throughout the power grid and send it to control centres where it is analysed and processed. These systems are composed of remote terminal units (RTUs) and master control units (MCUs). The RTUs collect data from sensors and send it to the MCUs, which process the information and allow operators to make informed decisions about the operation of the network [6]. They also allow remote control of circuit breakers and voltage regulators, improving fault responsiveness and reducing the need for manual intervention. The fundamental architecture of SCADA systems is shown below (Figure 2).

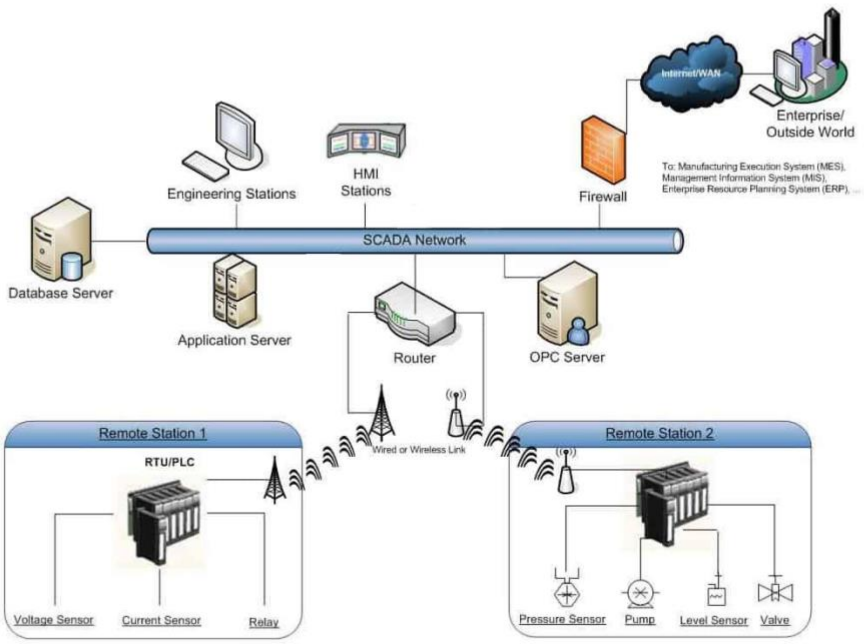


Figure 2. SCADA system architecture [7].

SCADA communications use protocols such as DNP3, IEC 60870-5-101:2003 (telecontrol and teleprotection) and IEC 61850 (automation), which ensure reliable and secure data transmission [6]. The integration of high-speed communication networks, such as fibre optics, improves the ability of SCADA to manage large volumes of data in real time.

2.1.1.2 Metering

Meters have evolved significantly since their origin, starting from the traditional electromechanical meters based on the Ferraris principle and patented in 1890 by Ottó Bláthy [6]. With the emergence of analogue and digital electronic circuits in the 1970s, electronic meters started to gain attention due to their low power consumption, high reliability and accuracy [6].

In addition, telecommunication technologies began to be applied to these meters, resulting in Automatic Meter Reading (AMR). AMR technology allows the automatic collection of meter data and its transmission to a central database for analysis, eliminating the need for manual readings and reducing the margin of human error [6].

2.1.1.3 Teleprotection

Teleprotection ensures the integrity of the grid by enabling a fast and efficient response to faults and anomalies. Teleprotection systems monitor the grid and send signals to isolate damaged sections, minimising the impact of faults and improving the reliability of the power supply. These systems include fault detection devices, communication units and fast-acting mechanisms that isolate affected sections of the network [6].

2.1.1.4 Other Traditional Applications

In addition to the three applications mentioned above, Smart Grids are traditionally used for video surveillance and other seity needs, intrasubstation telecommunications, mobile workforce telecommunications, and corporate telecommunications [6]. These applications are not discussed further, as they are not as relevant to the scope of the project.

2.1.2 NEW SMART GRIDS APPLICATIONS

As technologies evolve and the focus on sustainability increases, new applications have emerged expanding the capabilities of Smart Grids. These new applications range from Advanced Metering Infrastructure (AMI), Distribution Automation (DA), and Demand Response (DR) to Distributed Generation (DG) and cybersecurity.

2.1.2.1 Advanced Metering Infrastructure (AMI)

Advanced Metering Infrastructure (AMI) is an evolution of traditional metering systems and AMR, enabling bi-directional communication between smart meters and utility control centres [6]. AMI not only measures energy consumption, but also provides real-time data on power quality and other parameters.

AMI systems use a combination of communication technologies, including radio frequency mesh networks (RF Mesh), power line communication (PLC) and cellular networks [6], which enable the efficient transmission of real-time data from meters to control centres.

Smart meters within an AMI system can detect and report supply disruptions, monitor power quality, and enable the implementation of dynamic tariffs that incentivise efficient energy use. An AMI architecture is shown in Figure 3 below.

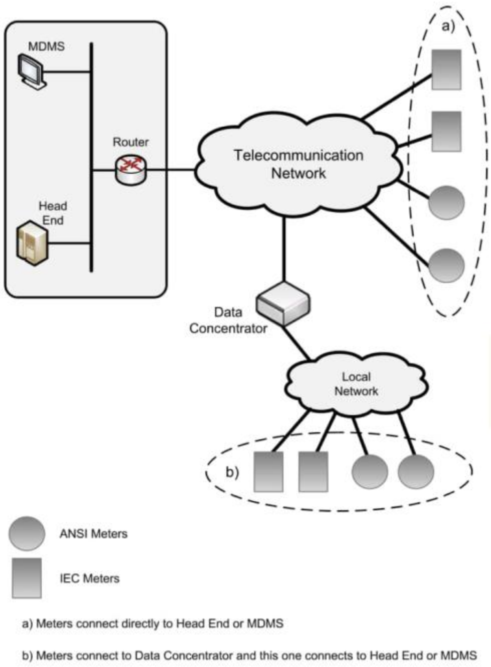


Figure 3. AMI Architecture [6].

2.1.2.2 Distributed Generation (DG)

Distributed Generation involves the integration of small power generation sources, located close to the consumption point, into the electricity distribution grid. This approach contrasts with the traditional model of centralised generation, where large plants generate electricity that is then transmitted over long distances.

The most prominent technologies in distributed generation are solar photovoltaics, wind turbines, fuel cells, biomass and electric vehicles [6]. The incorporation of these elements into the grid can change the traditional energy flow direction, as well as they may not generate electricity directly in alternating current. Due to these factors, new grid elements must be controlled by utilities.

The integration of DG in Smart Grids requires advanced remote monitoring and control capabilities to ensure grid stability and efficiency. Furthermore, fluctuations in renewable energy generation and harmonics generated by inverters (necessary for certain technologies for grid connection) can affect the quality of the power supply [6]. To avoid this, active and passive filters as well as voltage and frequency controls are used.

Moreover, cybersecurity is a critical aspect of DG integration, as remote monitoring and control systems are vulnerable to cyber-attacks, so it is necessary to ensure data integrity and confidentiality [6].

2.1.2.3 Distribution Automation (DA)

It involves the use of cutting-edge technologies to monitor, control and optimise the electricity distribution network. This includes substation automation, remote control of circuit breakers and regulators, and the implementation of self-recovery systems.

DA systems use a network of sensors and actuators scattered throughout the distribution network, which collect real-time data on various electrical parameters such as voltage, current, frequency and power quality. RTUs gather data from the sensors and send commands to the actuators [6].

DA relies on a robust and reliable communication infrastructure to transmit data between sensors, actuators and control centres. Communication technologies used in DA include fibre optic networks (offering high capacity and low latency), PLCs (using existing power distribution lines to transmit data, which is especially useful in areas where installing new communication infrastructure would be costly), and wireless networks (WiMAX, ZigBee and cellular networks are used to provide connectivity in areas where fibre optics or PLC are not practical) [6].

2.1.2.4 Demand Response (DR)

DR allows users' energy consumption to be adjusted in response to price signals or economic incentives, helping to balance energy supply and demand, and optimise the use of energy resources. They rely on smart meters, energy sensors and load controllers to collect, monitor and control real-time data on users' energy consumption [6].

Communication technologies used in DR include fibre optic networks, cellular networks (4G and 5G provide high-speed, low-latency connectivity) and PLC communication.

2.1.2.5 Cybersecurity

Cybersecurity is a component of Smart Grids responsible for protecting the power grid infrastructure against cyber-attacks, ensuring the confidentiality, integrity and availability of data [6].

The introduction of numerous electronic components in substations, two-way broadband telecommunications, the use of public networks and the complexity of architectures and operations [6] have forced the evolution of cyber security in electrical grids.

Smart Grids face several challenges in terms of cybersecurity. One of the main ones is the long-term nature of investments in electricity infrastructure, which makes it difficult to continuously update security measures. In addition, in systems where legacy operating systems are still in use, vulnerabilities are likely to be identified that cannot be corrected without a hardware upgrade.

Since Smart Grids are still at an early stage of development in many respects, there is no comprehensive and agreed technical and organisational approach to cybersecurity in the utility sector.

2.1.2.6 Electric Vehicles

The introduction of EVs in order to counteract the effect of fossil fuels and reduce pollution requires the electricity grid to be upgraded. The aim of Smart Grids is to reinforce the grid by strategically placing charging points, as well as to use these EVs as portable batteries meaning distributed energy storage.

2.2 PLC TECHNOLOGIES

Power line communications (PLC) is a telecommunications technology that uses power cables to transmit data, making it essential for the implementation of smart grids [5]. Despite its limited penetration in the general telecommunications market, PLC is widely used by utilities due to its ability to provide services in areas where other technologies have difficulties or require large investments.

Their first applications in the 19th century were related to meter reading and voice communication over power lines. Later, in the 1950s and 1970s, systems were developed for central load management and automatic meter reading (AMR), respectively [5]. From 1990 onwards, standards such as CENELEC's EN 50065-1 were established in Europe, which organised the spectrum used for PLC applications. Developments in the 2000s and 2010s introduced OFDM digital communication techniques, significantly increasing bit rates without increasing the bandwidth used [5].

PLC operates over existing power lines, in most systems using orthogonal frequency division multiplexing (OFDM) techniques to transmit data in parallel to the high power 50 or 60 Hz signal [5]. OFDM modulation allows PLC to divide the spectrum into multiple subcarriers, each modulated independently, which improves resistance to noise and interference.

Power cables are not designed for data transmission and therefore have several problems. Firstly, there is signal attenuation, which means that the signal can weaken along the transmission line. On the other hand, there is electromagnetic noise and interference (EMI) due to household appliances and other devices connected to the power grid that generate noise and interference that can affect signal quality. There is also the variation in the properties of the medium due to the continuous connection and disconnection of different loads that ends up changing the properties of the propagation medium [5].

To mitigate these problems, PLC uses advanced error correction techniques and adaptive modulation methods that dynamically adjust transmission parameters according to channel conditions.

2.2.1 ULTRA NARROWBAND PLC (UNB-PLC)

UNB-PLC refers to PLC technologies operating below 3 kHz. Within these technologies are ultra-low frequency technologies that operate between 0.3 and 3 kHz, and super-low frequency technologies that employ frequencies between 30 and 300 Hz [5].

Thanks to the use of such low frequencies, this technology is less affected by transmission losses, allowing a range of hundreds of kilometres, reaching beyond transformers, which allows its use in both medium and low voltage. However, the data rates of this technology are extremely slow, not exceeding 100 bps [5], which is its main limitation.

There are several cases of use of this technology, such as X10 in home automation since the 1970s [8], as well as Aclara TWACS (Two-Way Automatic Communications System) used in North America for AMI [8], to achieve remote reading of meters and direct load control.

2.2.2 NARROWBAND PLC (NB-PLC)

NB-PLC is the earliest and most mature PLC technology. It operates at frequencies between 3 and 500 kHz with intermediate data rates [5]. Depending on the data rate, two categories can be distinguished.

2.2.2.1 Low Data Rates (LDR NB-PLC)

This technology uses single-carrier modulation, which allows data rates reaching a few kbps. Its main applications include Smart Metering and Home Automation [5]. In relation to AMI deployments, the following technologies can be distinguished.

- Open Smart Grid Protocol (OSGP) is a protocol that has enabled the standardisation of the (PHY) and medium access control (MAC) layers by the IEC (International Electrotechnical Commission) [8]. It is widely adopted in the Nordic countries and Russia.
- Meters and More is an association belonging to the ENEL group that is dedicated to developing a communication protocol that is standardised by the IEC. It uses narrowband Binary Phase Shift Keying (BPSK) over PLC lines, achieving speeds of up to 4.8 kbps. Additionally, it implements encryption and authentication using a 128-bit Advanced Encryption Standard (AES) key [8]. This technology and its protocol are based on the IEC 61850 standard, which provides a unified framework for the automation of electrical substation, enabling interoperability and communication between devices from different manufacturers.

2.2.2.2 High Data Rates (HDR NB-PLC)

HDR NB-PLC uses several carriers for modulation, as is the case with multicarrier transmission. In this way, higher data rates are achieved than in the previous case, ranging from hundreds of kbps to a few Mbps [5]. The main proposals are presented below.

- PRIME v1.3 [5] [8] is a standardized solution as ITU-T G.9904 in which PHY and MAC layers are defined, as well as a convergence layer to interface with higher level protocols. PRIME uses an OFDM transmission system based on Fast Fourier Transform (FFT), with channel coding and differential phase shift keying (D-PSK). Transmission is carried out in the spectrum between 42 and 89 kHz, using 97 subcarriers per OFDM symbol. To reduce intersymbolic interference (ISI), the time sequence is extended with a cyclic prefix. The PRIME specification divides the Data

Link Layer (DLL) into two sub-layers: the MAC and the Logical Link Control (LLC). It defines two types of nodes: Base Node (BN), which manages network resources and connections, being unique per subnetwork, and Service Nodes (SN), which register with the BN to participate in the subnetwork. The transmission scheme is shown in Figure 4. The MAC layer also includes security and encryption, defining two security profiles. Profile 1 uses the Advanced Encryption Standard (AES) 128-bit encryption, ensuring privacy, secure authentication and data integrity. PRIME technology has been widely deployed in countries such as Spain, Portugal, Poland and Brazil, and continues to evolve to improve the efficiency and robustness of smart grid communications.

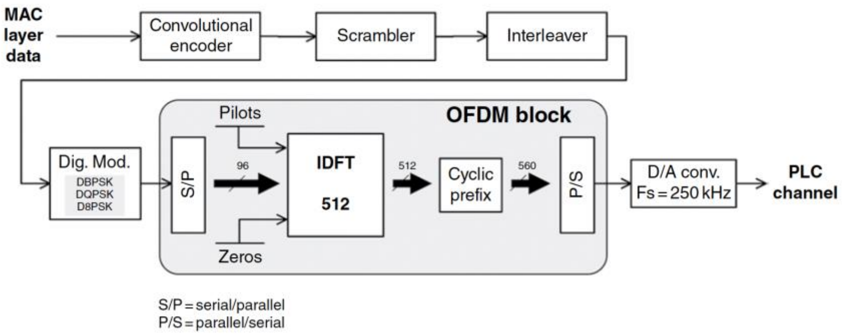


Figure 4. PRIME v1.3 transmission scheme [8].

- G3-PLC [5] [8] is a technical specification defined by the G3-PLC Alliance, sponsored by Electricité Réseau Distribution France (ERDF; now Enedis), with the purpose of supporting, promoting and implementing G3-PLC for Smart Grid applications. This is the ITU-T G.9903 standard in the same year, along with ITU-T G.9901, which covers the power spectral density and OFDM parameters used in G3-PLC. At the PHY layer, communication is based on data frames consisting of three main blocks: preamble, frame control header (FCH) and payload. It uses OFDM modulation with various digital modulation and channel coding options. Unlike PRIME, in G3-PLC some carriers can be dynamically disabled to avoid noisy bands, creating sub-domains. The MAC layer is based on the IEEE 802.15.4 specification and defines two priority levels for messages: high and normal. High priority messages use a specific contention window, while normal priority messages use a different contention window. The integrity of the transmitted data is ensured by acknowledgement (ACK) messages. Organises the network in a mesh topology with a Personal Area Network (PAN) Coordinator and several devices. It uses the Lightweight On-Demand Ad-hoc Distance-vector routing protocol – Next Generation (LOADng) to maintain end-to-end connectivity in the network. The transmission scheme is shown in Figure 5. Security at the MAC layer is based on a symmetric key shared by all nodes in the same PAN, ensuring privacy and authenticity of communications. G3-PLC focuses on increasing communication robustness through advanced channel coding techniques, which, while reducing the transmission rate, significantly improves noise resilience.

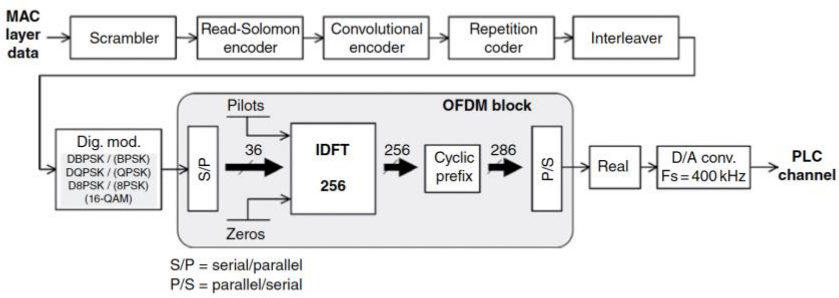


Figure 5. G3-PLC transmission scheme [8].

- IEEE 1901.2 [5] [8] was designed for NB-PLC in the frequency range 10-490 kHz. Influenced by ITU-T G.9904 (PRIME) and G.9903 (G3-PLC). At the PHY layer, the IEEE 1901.2 frame structure is like that of G3-PLC, with a preamble, a frame control header (FCH) and the payload. It uses an OFDM modulator and a pre-emphasis block to adjust certain carriers according to receiver feedback, improving the signal in highly attenuated frequency bands. The MAC layer shares mechanisms with G3-PLC, such as medium access and acknowledgement of messages (ACK). It introduces beacon-enabled and non-beacon-enabled modes and uses adaptive tone mapping to select the best carriers and modulation to ensure reliable communication. IEEE 1901.2 includes mechanisms for coexistence with other PLC technologies by dynamically changing the frequencies used and a preamble-based mechanism to minimise interference and allow fair coexistence of different PLC solutions in the same environment.

- G.hnem [5] [8] is the ITU-T G.9902 specification which focuses on NB-PLC below 500 kHz. It is influenced by features of previous PLC standards, such as PRIME and G3-PLC, and details the specifications for PHYs and DLLs for transceiver implementation. Transmission in G.hnem is based on OFDM modulation, using up-conversion to match the spectrum to the transmission band. Unlike other systems, it uses digital coherent modulation, which requires an equaliser at the receiver to handle the channel offset. This coherent modulation offers advantages in communication robustness, although it implies a more complex receiver. Furthermore, G.hnem incorporates FEC with a convolutional encoder and a Reed-Solomon encoder, which adds redundancy to improve transmission reliability. It also allows bit interleaving configurations to mitigate synchronous impulsive noise with alternating current, which further improves the robustness of the communication. The transmission scheme is shown in Figure 6. The DLL layer is responsible for managing access to the medium, ACKs security, network creation and interfacing with the higher layers. The network architecture is organised into domains, each with a domain master (DM) responsible for node admission and registration. Nodes in different domains can communicate via inter-domain bridges (IDBs). Access to the medium is implemented using a carrier sense multiple access with collision avoidance (CSMA/CA) algorithm with four priority levels, reserving the highest level for beacons and emergency messages. If enabled, access to the medium can be synchronous, with the DM sending periodic beacon messages to coordinate communications within the domain. G.hnem provides a robust solution for PLC, with a design focus on reliability and noise resilience, although field implementations of this standard have not yet been reported.

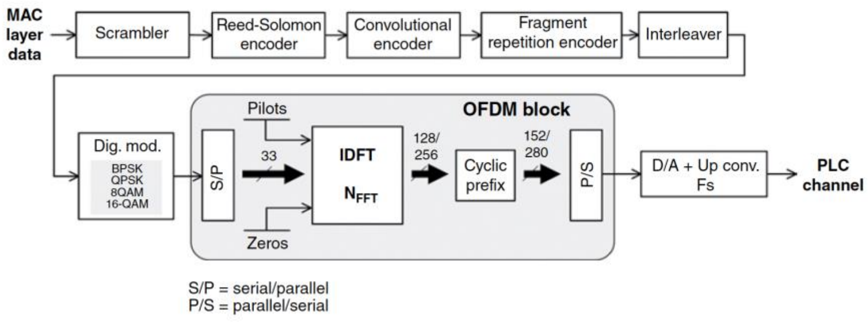


Figure 6. G.hnem transmission scheme [8].

2.2.3 BROADBAND PLC (BPL)

Broadband over Power Line is an evolution of the power line communication technology developed by AT&T Bell Telephone Laboratories in 1928. Originally, PLC was used for internal and low-speed communication applications within electric utilities, allowing data transmission over existing power lines [9]. This technology has been widely adopted in intercom systems and other equipment at customer sites, taking advantage of built-in electrical wiring to avoid additional special wiring costs.

In the 1990s, the development of BPL began, which has been standardized regionally ever since. Initial BPL systems coupled radio frequency data signals into existing power lines. These high-frequency signals are transmitted over the same lines that carry low-frequency electricity to homes or businesses, allowing both signals to coexist on the same cable [9]. This means that the basic idea of BPL is to modulate a radio signal with data and send it over power lines in a range of frequencies that are not used to supply electricity. The efficiency and speed of the BPL service depends significantly on the frequencies used and the coding scheme employed.

One of the most common coding schemes in BPL is Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a technique that allows large amounts of digital data to be transmitted over a radio wave by splitting the radio signals into multiple smaller sub-signals that are transmitted at different frequencies to the receiver. This method increases the speed and reliability of data transmission, as the distribution of data over multiple carrier frequencies simultaneously helps mitigate data loss caused by electrical interruptions when devices are turned on and off [9].

Another coding scheme used in BPL is Direct Sequence Spread Spectrum (DSSS). DSSS is one of two "spread spectrum" techniques in which a data signal at the transmitter is combined with a higher data rate bit sequence, or spreading code, which divides the user data according to a spreading ratio. This spreading code is a redundant pattern of bits for each transmitted bit, which increases the signal's resistance to interference. Data redundancy helps to recover bits that become corrupted during transmission [9].

BPL networks use technologies that transmit and receive signals using frequencies above about 2 MHz and up to several tens of megahertz, commonly about 30 MHz, although up to 250 MHz is achievable. While BPL can be applied to low voltage (LV) systems in many scenarios, it is mostly used in medium voltage (MV), as this part of the network is more controlled and predictable than LV [6].

The wide frequency range covered by this technology allows high data transmission rates reaching up to 250 Mbps, but at the cost of increased signal attenuation, which limits its range. Due to the higher attenuation, BPL is most used in short distance systems such as in-home networks and low interference environments such as MV networks [5].

In Europe and most of the world, PLC standards allow communications over the 220-240 V power grid at frequencies from 30 kHz to 150 kHz. In the United States, standards for the 120 V grid allow the use of frequencies above 150 kHz. Electric utilities use frequencies below 490 kHz for internal applications such as telemetry and remote substation equipment control and monitoring.

The main standards governing BPL communications are IEEE 1901, IEEE 1901.1-2018, ITU-T G.9960 (G.hn), as well as non-standardised protocols such as OPERA and HomePlug AV. These standards and technologies are discussed in more detail below.

- IEEE 1901 [5] [8] is a standard that provides high-speed communication solutions (up to 500 Mbps) over existing power lines, making it suitable for both internal home networks and last mile access applications [8]. 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 Fast Fourier Transform. In the 1.8-30 MHz band it uses 917 carriers for data transmission out of the 1155 available, maintaining backward compatibility with HomePlug AV 1.1, while in the 30-50 MHz band it uses 1974 carriers, maintaining the same carrier spacing as in the lower band. In both cases, the OFDM symbol duration remains at 40.96 µs. 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. Unlike FFT-OFDM, it does not require a cyclic prefix, which improves efficiency and reduces spectral leakage. 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. During the Contention Period (CP), CSMA/CA is used for general purpose devices, while the TDMA-based Contention Free Period (CFP) is intended for devices that require low latency or low jitter. The transmission block diagram proposed by IEEE 1901 is shown below. It is essential to mention that the IEEE 1901-2020 [21] 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.

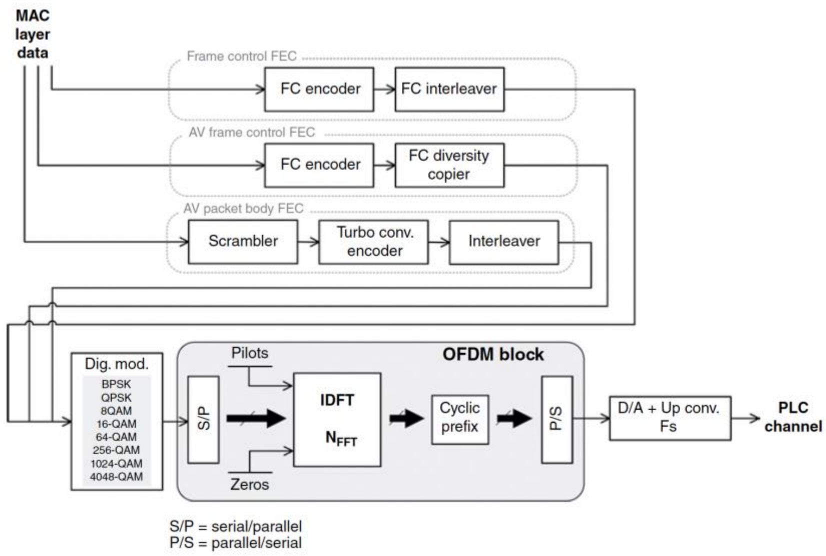


Figure 7. IEEE 1901 transmission scheme [8].

- 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. This standard is mainly used in Smart Grid applications, facilitating the transmission of critical and secure data over existing infrastructures. 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, prioritising certain types of traffic, and includes robust security mechanisms, ensuring the privacy of communications and their suitability for sensitive and critical services, including the ability to detect and mitigate unauthorised access attempts, protecting both the communication infrastructure and the transmitted data. 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 [20].

- ITU G.hn [5] [8] is the ITU-T 996x specification which emerged with the aim of achieving a transmission rate of up to 1 Gbps using two different profiles, one operating in the 2-50 MHz band and the other in the 2-100 MHz band. On the one hand, specifications were established for the PHY layer, using FFT-OFDM modulation combined with various digital communication techniques, which allows adaptation to different transmission scenarios. OFDM parameters, such as carrier spacing, sampling frequency and cyclic prefix length, are predefined in specific ranges to simplify implementations. Each OFDM carrier can be modulated with symbols of between 1 and 12 bits. The modulation of each carrier is independently adjusted according to the signal-to-noise ratio (SNR) and attenuation at that specific frequency, negotiated between the transmitter and receiver. employs an error correction mechanism based on a subset of LDPC (Low-Density Parity Check) codes, which includes several possible coding rates: {1/2, 2/3, 16/18, 20/21}. The ITU-T G.9963 recommendation adds the possibility to use Multiple Input Multiple Output (MIMO) capabilities, allowing higher transmission rates and improved coverage. In addition, for the MAC layer, a specification is developed indicating that ITU G.hn devices can be configured to operate in up to 16 different domains on the same or different physical media. Each domain has a Domain Manager (DM) that manages all devices in terms of resource allocation and priorities. Media access in ITU G.hn is coordinated by the DM through the MAC cycle, which can be synchronised with the main power cycle. This is beneficial for handling periodic changes in the channel or noise sources from electrical devices connected to the same network. Each MAC cycle is divided into several transmission opportunities (TXOPs), designated by the DM. These opportunities are dynamically adjusted, and the DM is responsible for configuring them and informing all nodes in the domain through the Media Access Plan framework. The allocation of TXOPs is based on device requests and depends primarily on the type of application running on the nodes, ensuring that critical applications receive a guaranteed level of quality of service.

- OPERA (Open PLC European Research Alliance) [3] [5] was established to provide a low-cost broadband access service to all European citizens using the most ubiquitous infrastructure, power lines. OPERA operates within a frequency range of approximately 2 to 28 MHz, with OFDM modulation, reaching data rates of 250 Mbps. In addition, it uses adaptive coding by dynamically adjusting the coding rate and modulation based on the conditions of the communication channel, thus optimising transmission efficiency and link robustness. It also implements MIMO techniques to improve transmission capacity by exploiting spatial diversity and enhance transmission reliability in interference and reflective environments.
- HomePlug AV [3] [5] is a technology whose products are fully interoperable with IEEE 1901-compliant products. It features several specifications, such as HomePlug AV, which operates in the 2 to 28 MHz frequency band using OFDM modulation, enabling bit rates of up to 200 Mbps. As well as HomePlug Green PHY which uses the 2 to 28 MHz frequency band and was designed specifically for applications related to the Internet of Things (home automation and control, home energy management systems and electric vehicle charging). HomePlug AV2 extends the operating frequency range to 1.8 to 87 MHz, enabling communication speeds of up to 1.5 Gbps, and includes enhancements such as MIMO capability.

2.3 POWER DISTRIBUTION SYSTEM

The distribution segment is one of the most complex parts of the smart grid due to its wide extension and variability. In European distribution networks, typical high voltage (HV) levels are 132 kV (110 kV in some regions) or 66 kV [6]. Below these levels, voltages of 30 kV, 20 kV and 10 kV are found in medium voltage (MV) networks, and levels below 1 kV in low voltage (LV) networks [6].

Medium voltage networks can be classified into three main types of topologies. Their structure depends largely on the trade-off between cost and reliability, with meshed and underground networks in urban areas, and radial and overhead networks in rural areas [10]. The radial topology consists of lines connecting primary substations (PS) with secondary substations (SS) in a tree-like configuration [6]. This topology has the advantage of being less costly to develop, operate and maintain, but it is less reliable, as a failure at any point can interrupt the power supply to several connected SS.

The ring topology improves reliability by connecting substations in a closed loop, allowing alternative routes for the power flow in case of failures [6]. This provides greater fault tolerance compared to radial topology, as it can be reconfigured to maintain supply, although it is more complex and costly to operate.

The networked topology connects multiple primary and secondary substations via various MV lines, providing numerous alternative routes for distribution. This topology offers maximum flexibility and reconfiguration options in case of failures, ensuring high reliability of supply [6]. However, it presents greater complexity in management, implementation and maintenance costs.

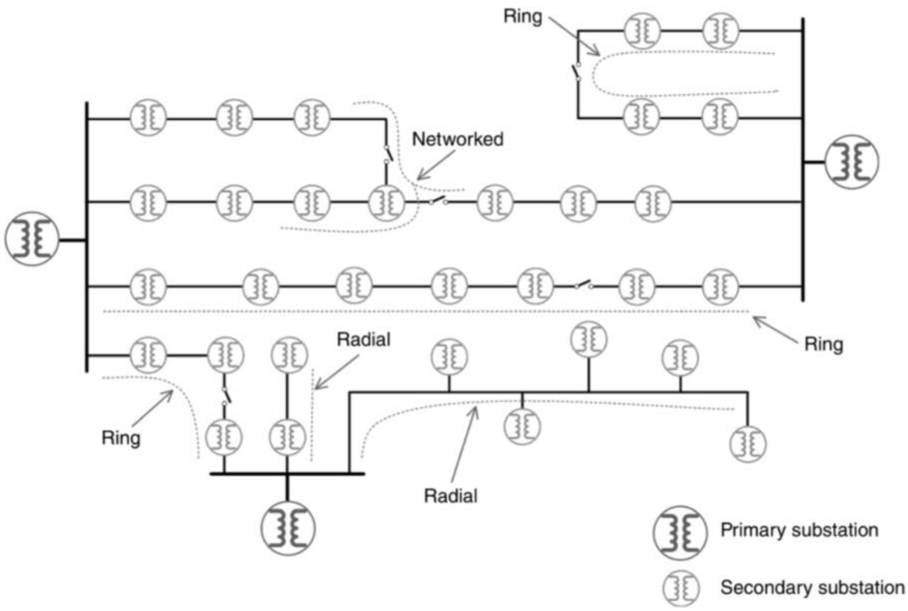


Figure 8. MV common topologies [5].

Low-voltage networks can be single-phase or three-phase, with three-phase networks commonly being 230V/400V in Europe, with users connecting between phase and neutral (4-wires) or between two phases (3-wires) [10]. LV network topologies are more varied and complex due to factors such as extension, load density, service area characteristics and international and utility regulations. Typically, a secondary substation feeds several LV lines with one or more MV to LV transformers, usually with radial topologies [6]. However, networked and ring configurations also exist in certain areas, depending on the specific needs and characteristics of the service.

Subsequently, the main elements found in distribution networks are discussed in more detail.

2.3.1 PRIMARY SUBSTATIONS

Primary substations are responsible for transforming high voltage to medium voltage by means of transformers. They contain circuit breakers, voltage transformers, control and surge protection equipment designed to direct the flow of electrical power, ensuring that it remains within safe and efficient parameters for the grid [6].

The voltage transformation can occur in several stages, with multiple substations involved [6], allowing a progressive reduction in voltage from the extremely high levels used in long-distance transmission to the lower levels suitable for distribution in secondary substations.

Their main functions are, firstly, safety, which means that substations are designed to isolate electrical faults and prevent them from propagating to the rest of the network [6]. This is achieved by circuit breakers and other protective devices that can quickly disconnect faulty parts of the system.

In terms of operation, a PS minimises energy losses and allows the separation of parts of the grid to perform necessary maintenance or install new equipment [6]. This capability is essential for maintaining the efficiency and reliability of the power grid, as it allows repair and upgrading without interrupting the power supply on a large scale.

Interconnection states that PS facilitates the connection of different electricity grids with different voltage levels, as well as the interconnection of several lines with the same voltage level [6]. This flexibility is crucial for the efficient management of power flow and to ensure grid stability.

In addition, primary substations are equipped to regulate voltage and compensate for system changes, switch transmission and distribution circuits, provide lightning protection and measure power quality. They also provide communication, control and protection devices, as well as equipment to control reactive power and perform automatic disconnections in case of faults [6].

2.3.2 SECONDARY SUBSTATIONS

Secondary substations are the points where electricity is transformed from medium voltage to low voltage for final distribution to consumers. These substations are located close to end-users to minimise energy losses and improve supply efficiency.

In Europe, secondary substations typically serve areas within a radius of a few hundred metres, while in North and Central America, distribution networks include numerous small distribution transformers that convert MV to LV and feed directly to one or several consumers via direct service cables [6].

The main components of a secondary substation include medium voltage lines, switchgear, transformers, low voltage panels and low voltage feeders. The MV lines are responsible for transporting electricity from the primary substations to the SS [6]. The switchgear or MV panels act as interfaces between the MV lines and transformers [6], providing both protection and the ability to disconnect and reconnect lines for maintenance or in the event of faults.

The transformer is the device that reduces the voltage from MV to LV levels. After the transformer, the LV panel splits the total power into several LV feeders, which are the lines that deliver the electricity directly to the consumers [6]. This configuration of the secondary substations can be found in detail in Figure 9.

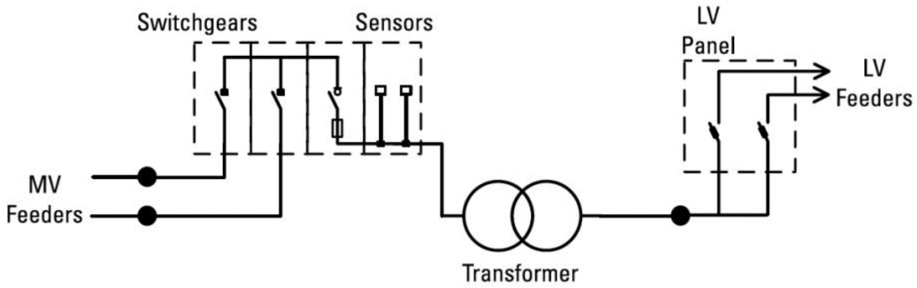


Figure 9. Secondary Substation scheme [6].

Secondary substations can be either indoor, which may be located in prefabricated shelters or integrated into larger buildings, or outdoor, which are common in rural and suburban areas and are typically configured with pole-mounted transformers, which facilitates access and maintenance. Indoor substations are designed to protect equipment from weather and other environmental factors and are usually located in basements or lower levels of buildings [6].

2.3.3 STREET FUSE BOX (SFB)

Street Fuse Boxes are components of low voltage electrical installations that are made of insulating material and house the protection elements of the General Supply Line (Línea General de Alimentación: LGA) [12]. They mark the boundary between the property of the electricity supply company and that of the end user. The regulation of SFB in Spain is defined by ITC-BT-13 of the Low Voltage Electrotechnical Regulation (Reglamento Electrotécnico de Baja Tensión: REBT), which establishes the technical conditions and guarantees that electrical installations connected to a low voltage supply source must comply with [3].

Their main objective is to ensure the safety of people and property, to guarantee the normal operation of electrical installations and to prevent disturbances to other installations and services. They are preferably installed on the external façades of buildings, in places that are freely and permanently accessible. In the case of overhead connections, SFB are installed superficially at a height of between 3 and 4 metres from the ground [12]. In the case of underground connections, on the other hand, SFB are installed in a niche in the wall and closed with a corrosion-protected metal door. Regardless of the type of service connection, the location chosen should be as close as possible to the public distribution network and away from or adequately protected from other installations, such as water and gas [12].

The basic structure of SFB includes fuses corresponding to each of the existing phases (one if single-phase and three if three-phase) and a removable copper connector for the neutral phase, which must always be placed on the left side of the box [12]. The final configuration of the SFB for each consumer is the responsibility of the distribution company. In Spain, SFB must also comply with the internal regulations of utilities such as Iberdrola, which has specific regulations such as Iberdrola Standard (NI) 76.50.01. This standard defines the SFB schemes used by the company, based on the options listed in the REBT. For example, scheme 1 is suitable for single-phase supply and schemes 7, 9, 10 and 11 for three-phase supply, with schemes 7 and 9 being the most common [3].

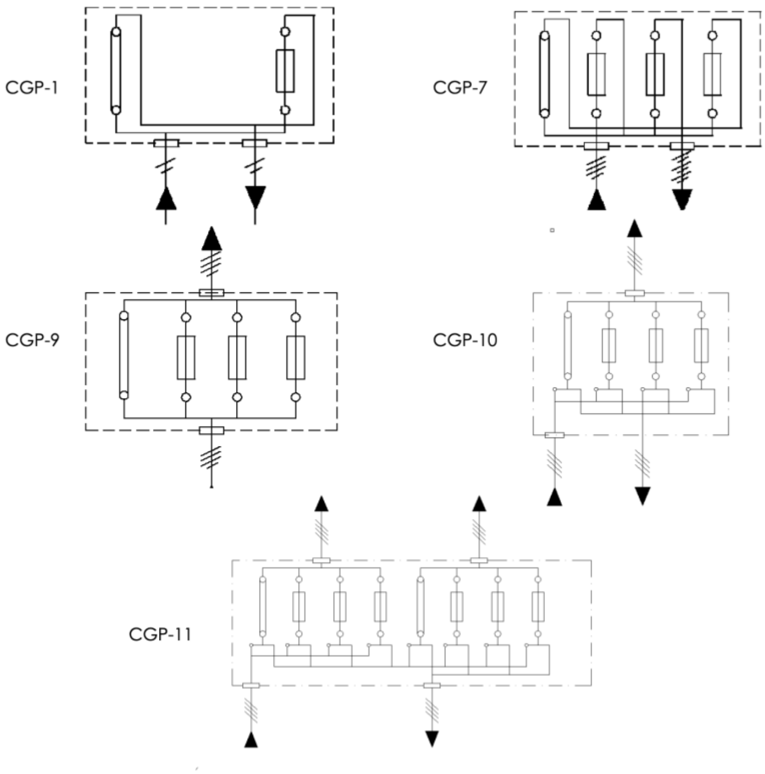


Figure 10. Standardised SFB [13].

2.3.4 MEDIUM VOLTAGE LINES

Medium voltage lines are responsible for carrying power from primary substations to secondary substations and other distribution points. These lines must be selected to provide a continuous power supply, capable of withstanding overload conditions and unforeseen demands [6].

A wide variety of MV cables are available, classified according to conductor material, cable cross-section and bunching type. Conductors can be made of either aluminium or copper, each with its advantages: copper is highly conductive, while aluminium is lighter and more economical [6]. The cross-section of the cable varies according to the power to be transported, with larger cross-sections being necessary for larger amounts of energy [6]. In terms of bundling, there are single-core, that have one conductor per cable, requiring three cables for each MV line, and three-core cables, which contain three conductors in a single cable [6].

The most relevant classification of MV cables is according to their location as overhead or underground lines. Overhead lines are installed on poles made of wood, steel, concrete or fibreglass, and may have one or more circuits per pole. Although today mainly aluminium is used for new overhead installations, there are still many copper lines in operation. These conductors, in turn, are divided into homogeneous, which are copper, all-aluminium (AAC) and aluminium alloy conductors (AAAC), and non-homogeneous, which include steel to improve mechanical strength, with types such as ACSR (aluminium with steel reinforcement) and ACAR (aluminium with aluminium alloy reinforcement) [6]. In addition, overhead lines can be bare (uninsulated, being the most common) or insulated (with polyethylene (PE) or cross-linked polyethylene (XLPE) coatings, offering greater reliability by reducing the risk of damage from vegetation or wildlife) [6].

Underground lines are more expensive to install, although they are considered safer and more reliable, with lower maintenance costs. These lines are composed of the conductor, the conductor shield, the insulation, the insulation shield, the neutral, or shield (sheath) and the jacket.

The conductor is made of aluminium or copper and can be solid or stranded. The conductor shield ensures a smooth radial electric field within the insulation, avoiding stress concentrations that could damage the insulation. The insulation is made of non-conductive materials such as PVC (polyvinyl chloride), PE, XLPE and EPR (ethylene propylene rubber), allowing the cables to withstand significant voltages with small diameters. The conductor is made of aluminium or copper and can be solid or stranded. The conductor shield ensures a smooth radial electric field within the insulation, avoiding stress concentrations that could damage the insulation. The insulation is made of non-conductive materials such as PVC (polyvinyl chloride), PE, XLPE and EPR (ethylene propylene rubber), allowing the cables to withstand significant voltages with small diameters. The insulation shield equalises the electric field at the interface between the insulation and the neutral or shield. The metallic sheath protects the cable from atmospheric discharges and fault currents, and the outer jacket protects all internal elements from mechanical and environmental damage [6].

2.3.5 LOW VOLTAGE LINES

Low voltage lines are components that are responsible for transporting power from secondary substations to end users. Unlike medium voltage lines, LV networks are more extensive and detailed, especially in Europe, where considerable investment is required for their proper documentation and management. Due to the complexity and extent of these networks, it is common for there to be gaps in utility records about the exact routes that LV lines follow, which customers are connected to which lines and to which specific phase they are linked [6].

In European secondary substations, the transformed power is connected to the LV panels via circuit breakers or isolating links. These panels manage and protect the outgoing LV lines. In densely populated urban areas, more complex LV networks are deployed, with cables running along pavements and interconnecting in underground junction boxes located at strategic points such as street corners [6]. These boxes allow LV lines to be distributed radially from the SS. In addition to underground junction boxes, LV distribution pillars and above-ground distribution cabinets, designed to withstand adverse weather conditions, can also be found. These cabinets mark the end of the network managed by the utility, with responsibility for the infrastructure beyond this point passing to the customer. Electricity meters are installed at these points, and in modern buildings, they are grouped in dedicated rooms that house all metering and protection devices [6].

In North and Central America, the distribution approach is different, as electricity distribution is mostly medium voltage, using three-phase systems feeding single-phase transformers. These transformers step down the voltage and distribute power directly to consumers via radial service cables or overhead lines [6].

LV lines can be either overhead or underground, with overhead lines using bare conductors or stranded cables supported by insulators and are often made of aluminium due to their lower cost and weight. In urban areas, underground LV cables are insulated with materials such as PVC, PE or XLPE and protected by an outer sheath, and can be installed in tunnels, ducts, tubes or directly buried in trenches [6].

2.4 GEOGRAPHICAL INFORMATION SYSTEM (GIS)

A Geographic Information System (GIS) is a tool that enables the collection, management and analysis of spatial data, based on geography, by organising the data into visualisations using 3D maps. GIS systems can be applied in multiple fields such as urban planning (assessing land use, transport networks and infrastructure), environmental management (managing and monitoring natural resources), agriculture (analysing soils and planning agricultural activities), and cultural heritage (mapping archaeological sites and managing historical records) [14].

In the energy sector, GIS is instrumental in creating a digital model of assets, obtaining valuable information on investments and risks, as well as reducing the time needed to obtain data on assets and facilitating the design of deployment and maintenance plans. This improves the operational efficiency of distribution companies [3].

EU Directive 2019/944 provided a framework and targets for modernising distribution networks in the EU. In October 2022, the EU Action Plan no Digitalizing the Energy System further advanced this by promoting the integration of renewable resources into the distribution grid, including the creation of a ‘digital twin’ of the power grid, which can be achieved through a GIS [3]. Companies such as Iberdrola use GIS for this purpose, facilitating the modernisation of their infrastructures.

At Iberdrola, the GIS used is MapInfo Professional version 12, which contains a set of tools such as the SICOID (Iberdrola Communications System) application. This tool makes it possible to compile and graphically represent all the company's telecommunications assets. The software shows the areas of Spain managed by Iberdrola and allows the selection of the type of telecommunications to be monitored, including transmission equipment such as

SDH, DWDM, MPLDS, SDN, fibre optics and radio. In addition, it features SIGRID which shows the medium and low voltage electrical network, together with trunking, earth leakage protection and secondary substations [3]. This is particularly useful for getting an overview of the low voltage network in both electrical and telecommunications terms.

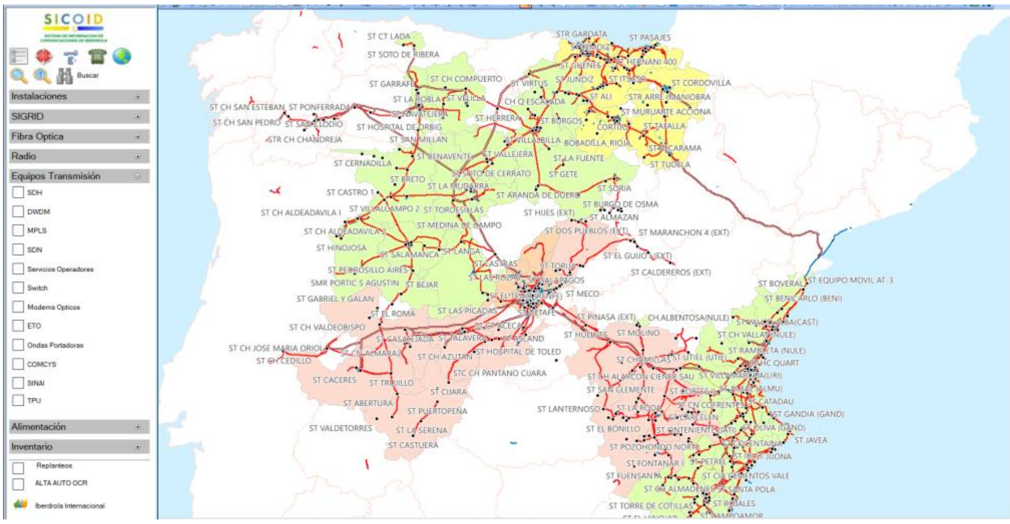


Figure 11. MapInfo and SICOID.

Chapter 3. STATE OF THE ART

Section 3 discusses the state of the art, which explores the implementation and challenges of Power Line Communication technology at various voltage levels, highlighting both narrowband and wideband networks. It examines the architectural differences between medium and low voltage networks, and how these specific characteristics influence signal propagation and PLC network design. Through detailed analysis, key BPL technologies and standards, such as ITU G.hn, IEEE 1901, HD-PLC and HomePlug, that enable advanced network digitization and distribution automation are described.

In addition, essential regulatory activities that ensure the safe and efficient operation of BPL equipment are addressed. These include general directives on the commercialization of electronic products, limits on conductive and radiated emissions, and immunity requirements for communication devices in low-voltage networks. Also discussed are the major technological, socioeconomic, and regulatory challenges facing BPL technology, such as radio frequency interference, network impedance variability, noise and unintentional emissions, transmission losses, and cybersecurity concerns. Finally, case studies and similar projects are presented that demonstrate the effectiveness and applicability of BPL in modernizing electrical infrastructures.

3.1 PLC AT DIFFERENT VOLTAGE LEVELS

Since PLC technology uses the power distribution lines themselves for data transmission, the architecture and design of PLC networks is heavily influenced by the specific characteristics of the power grid. Depending on different regions and segments, such as structure, topology, cable type, switching equipment, voltage levels and deployment practices, different architectures may be required for the same application [6].

PLC networks can be implemented in both medium-voltage and low-voltage networks, which present different topologies. In medium-voltage networks, overhead lines usually have a bus-type topology, and sometimes a meshed topology. Due to cost considerations, utilities often avoid installing additional nodes for redundancy, preferring linear topologies with point-to-point links between strategic nodes, such as transformer poles. This can be complicated by nodes connecting to multiple MV lines, creating star structures with splitting branches, forming arborescent topologies [6].

In the case of underground MV networks, a point-to-point topology is observed between transformers, with varying degrees of redundancy to handle power failures. These networks generally start at a secondary substation with a single backbone connection and follow a daisy chain structure up to points where several MV lines branch off, resulting in a final tree-like structure [6].

Low voltage networks, whether underground or overhead, present more complex topologies with multiple branches and sub-branches at various hierarchical levels. Although some branches connect to each other forming ring topologies, typically the LV network originates from a single source, usually a secondary substation. At this point a PLC master node is placed, and from there, PLC branches are deployed along the LV lines to the end points, which are the consumers [6].

Depending on whether the network is MV or LV, the propagation characteristics of PLC signals vary. Cable design and layout, as well as proximity to noise sources, significantly influence transmission quality. Overhead lines, for example, generally allow better signal propagation than underground lines due to less interference and better cable layout [6]. The installation of repeater devices is easier on overhead lines due to easy access to cables. In underground networks, these devices must be installed in accessible points such as fuse boxes, street cabinets or meter rooms, which can limit the options for signal amplification [6].

Power grids operate at frequencies of 50 Hz or 60 Hz, with power flowing from the MV segment to the LV segment through transformers. However, PLC signals operate at higher frequencies, which affects system planning, including frequency band selection and signal coexistence management. Low frequency PLC signals (below 10 kHz) can pass through transformers with some attenuation, allowing them to be detected at LV end points. In contrast, higher frequency signals (in the megahertz range) typically do not pass through MV/LV transformers, implying that MV and LV PLC networks should be treated as separate domains in terms of data transmission [6].

The selection of the appropriate PLC technologies for each network segment depends on several technical factors, such as the bandwidth required, existing infrastructure, availability of technologies and vendors, and utility preferences [6]. There is no one-size-fits-all solution for all networks, and it is common for MV and LV PLC networks to be considered physically separate.

3.1.1 NARROWBAND PLC NETWORKS

Narrowband power line communication networks represent one of the oldest and most mature communication technologies in the field of data transmission over power grids. Their initial application dates back almost a century, being used mainly by utilities in high-voltage networks for voice telecommunications and critical operations. Today, interest in NB PLCs has shifted towards applications in low-voltage networks [6].

a. NB-PLC over Medium-Voltage

The application of NB PLC in medium voltage networks began to take hold in the late 1980s, with joint efforts to standardise distribution automation (DA). This effort led to the IEC 61334 series of standards, which included the concept of distribution line carrier (DLC), as distinct from power line carrier, which was restricted to high-voltage lines [6].

Although NB PLC technologies in MV did not achieve significant success initially, due to the emergence of broadband over power line (BPL) technologies for LV, certain specific scenarios have shown value in their implementation. For example, in typical US distribution networks, where most of the network is MV, LV segments are limited in extent and number. In these cases, the NB PLC signal needs to cross transformers to connect different LV segments within the same network, which is achieved by simple passive devices [6].

b. NB-PLC over Low-Voltage

The most common use of NB PLC in smart grids is in smart metering applications over LV networks. This technology enables millions of smart meters to perform remote readings of measured values and manage internal switch connections and disconnections remotely [6]. In addition, it enables firmware upgrades of smart meters, making them dynamic nodes [6].

NB PLC channels in LV have been extensively studied, although it is difficult to formulate a universal channel model including stochastic noise applicable to any type of LV network. In the absence of a reliable model, the use of low-order modulations and simple but effective coding schemes is recommended. An example is the PRIME initiative, which in CENELEC A-band (3-95 kHz) configures transmissions at 20 kbps using differential binary phase shift keying (BPSK) and a ½ rate convolutional code. This scheme provides an adequate SNR margin to support instantaneous fading in LV channels [6].

Certain mechanisms are used to overcome the limitations of low-voltage NB-PLC channels. One of these mechanisms is segmentation and reassembly (SAR), which proposes to segment long packets into shorter packets and reassemble them at the receiver to increase the survival rate in NB PLC channels in LV [6]. Another mechanism used is the automatic repeat request (ARQ) at the MAC layer, which improves the robustness of transmission, but introduces an inherent overhead in each MAC layer packet [6].

NB PLC networks in LV generally have a master node that injects signals at the point of best access (MV/LV transformer in the secondary substation) to all relevant LV segments. These nodes can relay packets to other downstream nodes, improving coverage and reliability. Injection is typically performed in phase-to-neutral or phase-to-phase differential mode. The master node can also perform network management tasks, such as monitoring signal quality and implementing media access strategies to optimise communication [6].

In a typical configuration, the end nodes (such as smart meters) may not all be at an adequate distance to directly receive the signal from the master node due to physical and noise limitations in the LV network. With this technology, each node in the network can act as a repeater, relaying received packets to other nodes that are further away from the master node [6]. This process allows signals to reach nodes that would otherwise be out of direct communication range. Therefore, improved coverage (without increasing the initial signal strength), increased redundancy and reliability, as well as optimised bandwidth are achieved.

3.1.2 BROADBAND PLC NETWORKS

Broadband power line communication networks emerged in the 1990s as an alternative for data transmission, offering a solution to leverage existing electrical infrastructure for high-speed communication, as it uses frequencies ranging from approximately 2 MHz to several tens of megahertz [6]. As the demand for bandwidth grew exponentially with the expansion of the Internet and digital services, BPL emerged as a viable option for bringing connectivity to areas where other forms of access were limited or expensive.

Although the implementation of BPL can encompass both LV and MV networks, this section will initially focus on the use of BPL in MV due to the more controlled and predictable conditions of these networks compared to LV networks. Its application in MV grids provides a robust and efficient means for data transmission, vital for the modernisation of power grids and the development of Smart Grid.

a. 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, therefore specific frequency division multiple access (FDMA) or time division multiple access (TDMA) technologies are considered [6]. OPERA technology has proven to be effective in large-scale deployments, implementing TDMA domains of limited size that coexist using an FDMA approach, ensuring non-interference between nearby TDMA domains [6].

To optimise the use of available frequencies, two main frequency modes are defined. Mode 1 uses the 2 to 7 MHz range, while Mode 2 operates in the 8 to 18 MHz range [6]. Thus, both modes offer similar bandwidths in real deployments due to the channel characteristics.

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].

Signalling coupling is fundamental to the deployment of BPL in MV networks. This process involves injecting BPL signals into the MV network so that they propagate through the network to the desired destinations. BPL couplers allow high-frequency signals to be superimposed on the power waveform, while preventing the latter from entering the transceiver and causing interference [6].

Inductive coupling is flexible and economical, and these couplers are electrically isolated from the power cables and are installed around an MV phase cable. Connected through a 50 Ω coaxial connector, these couplers, however, can be ineffective in situations where the line impedance varies, especially when the breakers are open, limiting their use in MV BPL [6].

Alternatively, capacitive coupling is more common in smart grid applications due to its higher reliability. These couplers allow efficient coupling of high-frequency waveforms and are ideal for installations in open-air and enclosed metal switchgear. Although more expensive, they offer better performance, especially in the lower range of the BPL frequency band.

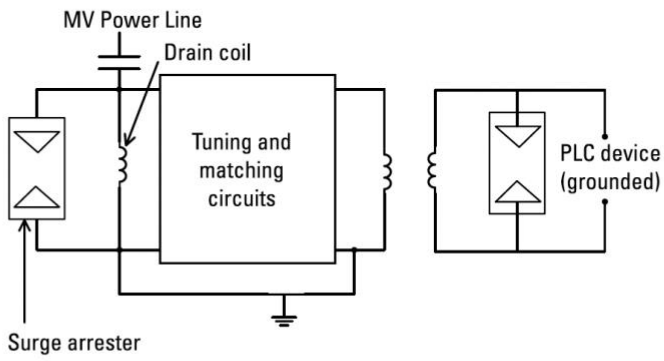


Figure 12. MV capacitive coupler [6].

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].

b. 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 [11].

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. These factors are detailed below.

- Topological complexity [11]: 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 [11]: 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 [11]: 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 [11]: 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 [11]: 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.

3.2 FUNDAMENTALS OF BPL OVER LV

In this section, the main features of the most relevant BPL technologies applicable to the low voltage distribution network, which are relevant to the project, are described. These are fundamental to the digitalization of the network, including distribution automation and advanced metering infrastructure. Some of these standards or technologies were previously described in Section 2.2.3, but this section focuses on their application in low voltage.

3.2.1 GIGABIT HOME NETWORKING (ITU G.HN)

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 [15].

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 [15].

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 [15].

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 [15].

3.2.2 IEEE 1901

The IEEE 1901-2010 standard is the result of the work of the IEEE P1901 group and combines proposals from the HomePlug Powerline Alliance and the HD-PLC Alliance. It enables high-speed communications with data rates up to 100 Mbps in the frequency range from 1.8 MHz to 50 MHz [15].

For the physical layer, it uses both FFT-based OFDM and Wavelet-based OFDM, offering robustness against narrowband noise and frequency selective channels. In addition, in the IEEE 1901-2020 revision, a Flexible Channel Wavelet (FCW) PHY is included, enabling high-speed, long-distance communications for IoT applications [15].

At the MAC layer, a coexistence protocol (CXP) is defined to allow coexistence of IEEE 1901 compliant and non-compliant devices, as well as other systems such as ITU-T G.hn. It offers connection-oriented and connectionless services, using TDMA and CSMA/CA to manage access to the medium [15].

3.2.3 NESSUM (FORMERLY HD-PLC)

NESSUM, formerly known as HD-PLC, has evolved through four technology generations, each adapting to different application scenarios. The third generation is divided into HD-PLC3 Complete and HD-PLC3 Multi-hop.

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 [15].

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 [15].

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 [21]. 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.

3.2.4 HOMEPLUG

The 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 [15].

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 [15].

3.2.5 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 [15].

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 [15].

3.2.6 KS X 4600-1

The KS X 4600-1 standard, adopted by ISO and IEC in 2009, defines both PHY and MAC layers to support IEEE 802.3 and serial protocols. The physical layer uses discrete multi-tone modulation (DMT) in the 2.15 MHz to 23.15 MHz range, with adaptive modulation of DBPSK, DQPSK, or D8PSK, and error correction mechanisms such as Reed-Solomon and convolutional coding. The MAC layer uses CSMA/CA as the access technique and IEEE 802.3 MAC addresses [15].

3.3 REGULATORY ACTIVITIES FOR BPL

The implementation and development of Broadband over Power Line technology in low voltage networks is subject to several regulatory directives and standards designed to ensure its safe and efficient operation. This chapter describes the main regulations and standards that must be considered in the development of BPL equipment, ranging from electrical waste management to emission limits and immunity requirements.

3.3.1 DIRECTIVES OF GENERAL APPLICATION

The European Union has defined several directives on the marketing of electronic products which, although of general application, also affect BPL products. A schematic summary of these directives can be seen in Figure 13.

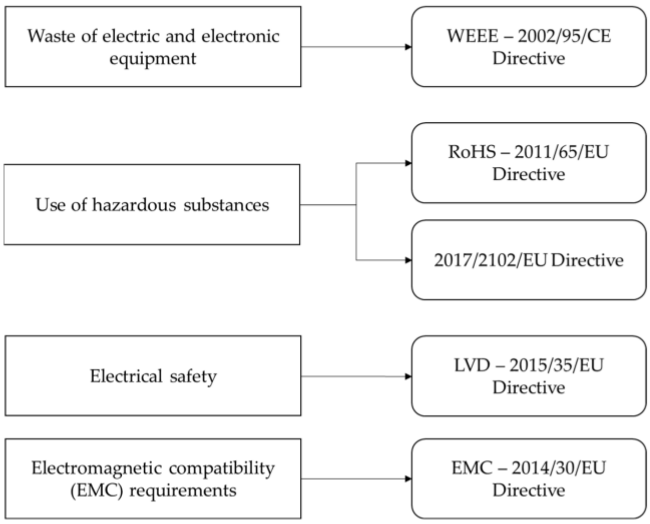


Figure 13. Directives to be considered in the development of BPL devices [15].

- Waste Electrical and Electronic Equipment Management is implemented through the WEEE - 2002/95/C Directive which focuses on the reduction of waste electrical and electronic equipment through reuse, recycling and other forms of recovery of such equipment. It establishes responsibilities for producers, who must finance the collection and proper treatment of electronic waste. The directive also promotes the design of products that are easier to recycle and repair [15].

- Restriction of the Use of Hazardous Substances is addressed through the RoHS - 2011/65/EU Directive and 2017/2102/EU Directive. They restrict the use of certain hazardous substances in electrical and electronic equipment to protect public health and the environment. Specifically, they limit the use of materials such as lead, mercury, cadmium, hexavalent chromium, and various brominated flame retardants. RoHS 2017/2102/EU updates and expands the restrictions of the original 2011 directive to include more products and substances [15].
- Electrical Safety is addressed in the LVD - 2015/35/ EU Directive (Low Voltage Directive) which regulates safety requirements for electrical equipment operating at voltages between 50 and 1000 V for alternating current and between 75 and 1500 V for direct current. It ensures that products do not present risks to people, pets or property by establishing standards on design, manufacturing and safety documentation [15].
- Electromagnetic Compatibility Requirements are regulated by the EMC - 2014/30/EU Directive which sets out requirements to ensure that electrical and electronic equipment operates correctly in its electromagnetic environment and does not cause unacceptable electromagnetic interference to other equipment. The directive covers everything from the emission of electromagnetic radiation to the immunity of equipment from interference [15].

3.3.2 CONDUCTIVE AND RADIATED EMISSION LIMITS

Conductive and radiated emissions are important issues in the development of BPL equipment. Relevant European standards define limits and measurement methods to ensure that devices do not interfere with other communication services. In terms of conductive emissions, two standards are encountered:

- EN 50561-1:2013+AC:2015 that specifies limits and methods of measurement of conductive disturbance characteristics at PLC ports for home communication devices that use LV power installation as transmission medium. Applies to equipment communicating in the frequency range of 1.6065 MHz to 30 MHz. Limits are measured using a line impedance stabilization network (LISN) to ensure consistency and accuracy of measurements. Disturbance levels must comply with CISPR 11:2015 Class B [15] limits designed for devices suitable for use in residential areas as it can be observed in Table 1.

Fraquency Range (MHz)	Limits (dBµV)	
	Quasi-Peak	Average
0.15 to 0.50	66 to 56	56 to 46
0.50 to 5.00	56	46
5.00 to 30.00	60	50

Table 1. Class B limits for conducted distrubances [15].

- EN 50561-3:2016 which covers the same aspects for equipment communicating using BPL in a frequency range above 30 MHz, typically between 30 MHz and 118 MHz. Although this standard is not yet included in the list of harmonized standards of the EMC Directive [15].

For radiated emissions, the standard followed is EN 55032 which does not specify limits for radiated disturbances in the frequency range from 150 kHz to 30 MHz. For frequencies above 30 MHz, radiated emission limits defined for class B equipment apply, which are applicable from 30 MHz to 1 GHz. These limits are measured using quasi-peak detectors with a bandwidth of 120 kHz and are specified for measurement distances of 3 or 10 meters in open area test sites (OATS) or fully anechoic chambers (FAR) [15]. These constraints are presented in the table below.

Frequency Range (MHz)	Measurement			Limits (dBµV/m)
	Equipment	Distance (m)	Type of Detector/Bandwidth	
30 to 230	OATS/SAC	10	Quasi-peak /120 kHz	30
230 to 1000				37
30 to 230	OATS/SAC	3		40
230 to 1000				47
30 to 230	FAR	10	Quasi-peak/120 kHz	32 to 25
230 to 1000				32
30 to 230	FAR	3		42 to 35
230 to 1000				42

Table 2. Class B limits for radiated distrubances [15].

3.3.3 PLC TRANSMITTED SIGNAL LIMITS

The EN 50561-1 standard establishes the maximum signal levels transmitted by PLCs in the frequency band from 1.6065 MHz to 30 MHz. BPL devices must incorporate a dynamic power control function to minimize radio disturbances while maintaining effective communication. The specified limits ensure that transmitted signals do not interfere with other communication services in the same frequency range.

Symmetrical Mode Insertion Loss EUT to AE in dB	10	20	≥40
Maximum Transmit Signal Level in dB (µV) (AV)	65	75	95
Maximum Transmit Signal Level in dB (µV) (PK)	75	85	105

Table 3. Maximum PLC transmit level [15].

3.3.4 IMMUNITY REQUIREMENTS

Immunity requirements for communication devices in LV installations in the frequency range 1.6 to 30 MHz are specified in EN 50412-2-1:2005 CORR: 2009 [15], which includes:

- 50 Hz Power Frequency Magnetic Field [15]: Ensures that devices operate correctly in the presence of power frequency magnetic fields.
- Amplitude Modulated Radio Frequency Electromagnetic Field [15]: Protects against interference from radio frequency electromagnetic fields.
- Electrostatic Discharge [15]: Defines the resistance to electrostatic discharge to prevent damage and equipment failure.
- Radio Frequency Conducted Continuous Common Mode [15]: Ensures that the equipment is immune to radio frequency conducted disturbances.
- Voltage Drops and Interruptions [15]: Ensures continuous operation during voltage fluctuations.
- Surges [15]: Protects against sudden voltage surges that can damage equipment.
- Fast Electrical Transients [15]: Ensures resistance to fast transient disturbances in the electrical network.

3.4 CHALLENGES FOR BPL

BPL technology faces several challenges in its implementation and operation in low-voltage networks. These challenges encompass technological, socioeconomic and regulatory aspects, and require comprehensive solutions to ensure the viability and effectiveness of BPL. These challenges and possible solutions are detailed below.

3.4.1 TECHNOLOGICAL CHALLENGES

a) Radio Frequency Interference (RFI)

RFI is one of the biggest obstacles for BPL since these signals operate in the 1.7 to 80 MHz range, which can cause mutual interference in licensed frequency bands such as those used by amateur radio and emergency services. The FCC in the United States and the European Commission have established guidelines to mitigate RFI. These include the implementation of adaptive mitigation techniques such as dynamic reduction of transmit power and avoidance of specific frequencies [9].

b) Grid Impedance

The impedance of the electrical network varies depending on the topology and connected devices, affecting the propagation of PLC signals. Impedance variations can cause mismatches that limit power transfer and communication efficiency. Accurately characterizing network impedance through extensive field testing in different scenarios is essential, including the development of measurement methods specific to LV network conditions and the creation of a metrologically traceable network impedance standard, allowing objective comparison of measurement techniques [15].

c) Noise and Non-Intentional Emissions (NIEs)

The LV network is subject to high levels of noise and impulsive emissions generated by electronic devices such as electric vehicle chargers and solar panels. These emissions can significantly interfere with BPL communications, so it is necessary to develop statistical models to characterize network noise and employ advanced noise mitigation techniques. Recent measurement campaigns have identified the main sources of NIE and characterized their properties, providing a basis for the development of specific solutions [15].

d) Transmission Losses

Transmission losses in the LV network increase with frequency, limiting the effective transmission distance of BPL signals. Network splits into different branches generate 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. Implementing robust coding techniques, such as LDPC codes, can help overcome attenuation limitations, albeit at the cost of reducing the net data rate [15].

e) Channel Modelling

Accurate modelling of the transmission channel is crucial for BPL deployment. There are two main approaches: the top-down approach, based on measurements, and the bottom-up approach, based on transmission line theory. Both approaches must be applied to obtain a detailed and accurate model of signal propagation in the LV network. It is also essential to carefully select the band in which the PLC signal achieves the best signal-to-noise ratio (SNR). Using equipment power in noisy bands leads to inefficiency, as the signal may be drowned out by noise. Therefore, combining empirical models based on measurements with theoretical models ensures that propagation effects, including frequency-dependent attenuation, multipath effects and selection of the optimal band for SNR, are adequately represented. [15].

f) Limitations of the Propagation Medium

The power grid is a hostile transmission medium due to the presence of interference, electrical noise and signal attenuation. The characteristics of the cabling and connections can cause significant signal losses, limiting the efficiency of data transmission. Develop detailed models of power grid behaviour in the frequency range used by BPL, including field studies and simulations to identify and mitigate sources of signal loss. The implementation of advanced modulation techniques, such as OFDM and DSSS, can help improve the robustness of transmission in this medium [15].

g) Cybersecurity

The digitalization of the power grid increases its vulnerability to cyber-attacks, as sensitive data on consumption and grid quality must be adequately protected to prevent unauthorized access and ensure user privacy. Implement robust encryption techniques and advanced security protocols, such as the EAP-TLS (Extensible Authentication Protocol - Transport layer Security) authentication protocol and encryption of authentication messages. It is also essential to develop methods to detect and mitigate attacks in real time. Network-connected devices must meet strict security standards and receive regular updates [15].

3.4.2 SOCIO-ECONOMIC CHALLENGES

a) 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 [9].

b) 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 [9].

3.4.3 REGULATORY CHALLENGES

a) Industry Governance Issues

Coordination between electricity and telecommunications regulators is vital to ensure that there are no unnecessary regulatory obstacles to BPL deployment. Lack of coordination can lead to duplication of efforts and regulatory inconsistencies that hinder the implementation of the technology.

The FCC has established rules to protect against radio frequency interference (RFI) and has created public databases to address interference problems. These rules require BPL devices to employ adaptive mitigation techniques to prevent harmful interference to existing users, and to maintain a public database with information on the location, operating frequencies and modulation type of BPL devices. Furthermore, the European Commission has mandated standardization bodies such as ETSI and CENELEC to develop harmonized EMC standards for wired telecommunications networks, including BPL. These standards are essential to ensure that BPL systems do not interfere with other users of the radio spectrum [9].

The proximity of BPL equipment on utility poles can affect (and be affected by) the operation of cable television and high-speed digital transmission services, such as DSL. The European Commission's recommendations include implementing interference management systems according to the requirements of the EMC Directive and ensuring that BPL networks comply with harmonized standards developed by ESOs [9].

b) Regulatory Classification & Treatment Issues

One of the main regulatory challenges for the implementation of BPL is the lack of clarity in its classification and treatment within existing regulatory frameworks. In many countries, utilities have the potential to become telecommunications service providers using BPL infrastructure, but this requires a regulatory environment that enables and encourages such a transition [9].

In the U.S., the Federal Communications Commission has classified BPL as an "information service," which aligns it with other broadband and cable services. This exempts BPL from certain open access requirements that apply to other forms of telecommunications, making it easier for utilities to deploy. Moreover, in Europe, BPL is regulated under the same regulations as telecommunications networks, following the Telecommunications Framework Directive 2002/21/EC. This means that companies with significant market power must comply with rules such as local loop unbundling and number portability, designed to promote competition in the telecommunications sector [9].

The European Commission has recommended that member states remove unjustified regulatory obstacles, especially for utilities seeking to deploy BPL systems. his includes ensuring that BPL networks comply with harmonized standards developed by European standards organizations (ESOs), such as ETSI and CENELEC, to avoid interference with other users of the radio spectrum [9].

In addition, access to physical infrastructures such as poles and conduits is essential for BPL deployment. In many OECD countries, utilities must allow access to these infrastructures for any entity that requests it, if they are already used for communications services. However, in some regions, utilities have avoided this regulation by not allowing communications services to be transmitted over their poles [9].

3.5 BENCHMARK OF SIMILAR PROJECTS

This section looks at various projects that implement BPL technology to improve the management and operation of electricity grids. Three main projects are addressed: 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 standardised by the PRIME Alliance to validate the effectiveness of BPL in different contexts. These projects demonstrate the technological resilience, process maturity and operational efficiency of BPL, highlighting its ability to provide real-time and secure communication and to handle large volumes of data in modern energy infrastructures.

The first project focuses on the deployment of thousands of BPL links in medium-voltage grids, demonstrating their ability to provide smart grid services with high levels of performance and reliability. The second project, led by E.ON, uses Corinex's BPL technology to facilitate communication between smart meters in Germany, validating its viability and efficiency in a low-voltage environment. Finally, the PRIME Alliance has standardised several BPL use cases, including integration with smart meters and co-existence with NB-PLC technologies, to demonstrate its applicability and benefits in various grid configurations. These studies underline the importance of BPL as a key technology for the evolution of electricity grids towards smarter and more resilient systems.

3.5.1 BPL OVER MEDIUM VOLTAGE AS MULTISERVICE BACKBONE

This study analyses the deployment of thousands of BPL links in medium voltage grids to provide smart grid services, demonstrating high technological resilience, process maturity and operational efficiency [6].

The design of the BPL network must be adapted to the specific characteristics of the medium-voltage network, including topology, cable type and switching equipment. It is also necessary to align these criteria with the BPL technology specifications, such as frequency ranges and data rates. To validate these criteria, a pilot was carried out in a representative area, installing BPL devices and couplers, and performing performance measurements [6].

During this pilot, several initial conditions were set, such as the exclusive use of medium voltage underground cables and the need to achieve a minimum two-way data rate of 100 kbps at each secondary substation [6]. The results confirmed that these values were adequate for the real network, achieving the expected performances.

Approximately 14,000 BPL devices were installed in the field, with an increase of 150 devices each week. Statistical results fully validated the design criteria. More than 40% of the BPL links achieved throughput rates between 30 and 50 Mbps, with an average latency of 10 to 20 ms per BPL hop [6]. These results demonstrate that BPL technology can provide reliable and efficient performance in the medium voltage network.

3.5.2 E.ON USES CORINEX BPL

In 2018, E.ON, a power grid, customer solutions and renewable energy company, initiated an ambitious project to implement BPL technology as a means of communication between smart meters in the low-voltage grid in Germany. Its main objective is to ensure real-time communication and a secure network. This initiative employs Corinex's BPL technology, together with MaxLinear chipsets and the IBM Tivoli network management solution [16]. The technology adopted follows the ITU G.hn standard.

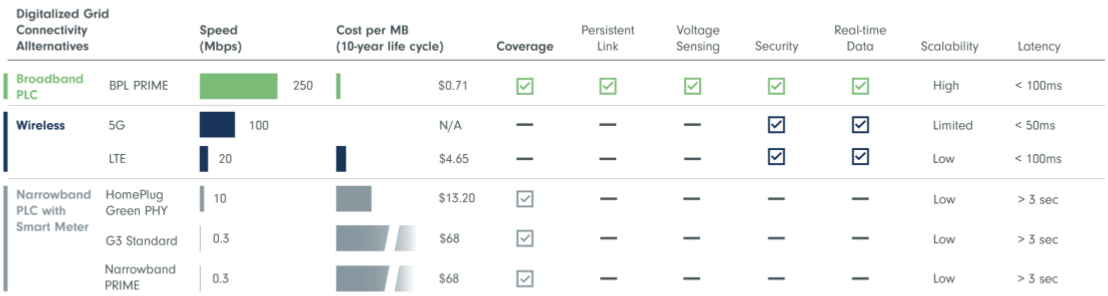
During the first two years, the project focused on a pilot phase that included the deployment of approximately 10,000 repeaters and headends, covering several hundred thousand households [16]. The results of this initial phase were positive, demonstrating that the technology met the necessary requirements for smart metering services.

Corinex, a world leader in delivering grid resilience solutions through BPL, provides a full suite of products specifically designed for E.ON, including GridValue, which combines grid management hardware and software to enable fast and secure smart meter connectivity, grid monitoring and IoT management using existing power line infrastructure [17].

In addition, a digitisation solution that offers reliable communication, computational capacity and security is crucial for a flexible and resilient network. Current centralised communication infrastructures, which use NB-PLC, have limitations in terms of data capacities and energy security. In contrast, a decentralised network, with BPL, enables multi-directional communication, dynamically balancing load and power generation through real-time energy data, analytics and predictive modelling [17].

Figure 14. Centralized vs self-regulating digitalized grid [17].

This project concludes that BPL technology represents a significant improvement over NB-PLC technology, which is currently preferred in many global markets. These BPL solutions not only offer a superior and cost-effective connection compared to competing technologies, but also represent the next step in the evolution of PLC technologies, replacing NB-PLC units over the natural upgrade cycle [17]. The integration of BPL technology offers several advantages over NB-PLC technology, including faster and cheaper connection. The image below shows the advantages of BPL over other technologies, highlighting coverage, security, latency and real-time data.



Digitalized Grid Connectivity Alternatives		Speed (Mbps)	Cost per MB (10-year life cycle)	Coverage	Persistent Link	Voltage Sensing	Security	Real-time Data	Scalability	Latency
Broadband PLC	BPL PRIME	250	$0.71	☑	☑	☑	☑	☑	High	< 100ms
Wireless	5G	100	N/A	—	—	—	☑	☑	Limited	< 50ms
	LTE	20	$4.65	—	—	—	☑	☑	Low	< 100ms
Narrowband PLC with Smart Meter	HomePlug Green PHY	10	$13.20	☑	—	—	—	—	Low	> 3 sec
	G3 Standard	0.3	$68	☑	—	—	—	—	Low	> 3 sec
	Narrowband PRIME	0.3	$68	☑	—	—	—	—	Low	> 3 sec

Figure 15. Comparison between different technologies [17].

E.ON's project with Corinex not only validates the feasibility of BPL technology for smart metering, but also promotes a more efficient, secure and adaptable power grid for modern energy challenges, helping the industry to meet today's climate and energy challenges more effectively.

3.5.3 OTHER BPL USE CASES

In December 2018, the PRIME Alliance established four use cases for BPL technology to develop together with Corinex, an interoperability specification to shed light on the deployment of this technology and set specific performance requirements [18]. These use cases have been adopted by several utilities in Europe to field test and validate the effectiveness of BPL technology.

- *BPL Smart Meters with BPL Concentrator*

This use case involves a complete BPL metering chain, where a BPL smart meter acts as an endpoint and a data concentrator as a controller. A notable example is ČEZ Distribuce, a major European distribution system operator that has combined BPL with machine learning algorithms to predict residential loads and solar energy production. This integration has reduced energy peaks, improving grid efficiency and optimising energy resource management [18].

- *Coexistence of BPL and NB-PLC*

This use case allows network operators to use broadband BPL concentrators and gateways alongside their installed base of NB-PLC smart meters. This coexistence facilitates the transition to more advanced technologies without the need to immediately replace the entire existing infrastructure. Iberdrola is testing this integration in the low-voltage part of its network, moving narrowband concentrators into buildings to improve network management [18].

- *BPL Smart Meter Gateway with Voltage Detection*

Voltage sensing is key to identifying grid problems, reducing equipment investments, improving quality of service and reducing the system's carbon footprint. E.ON has led this effort, considering various communication options and testing different BPL providers. Finally, they chose Corinex for their first wave of deployment, which started at the end of

2019. As previously explained, this deployment included more than 100,000 network elements, all managed through high-availability software [18].

- *BPL on MV Lines*

This use case explores the possibility of using medium voltage lines to carry data traffic, as an alternative to fibre optic or wireless networks. This is particularly relevant for demand response applications and the integration of electric vehicles into the grid, which require reliable real-time connectivity for millions of IoT devices. Iberdrola has deployed more than 25,000 BPL devices at medium voltage, demonstrating the technology's ability to handle large volumes of data and support advanced applications [18].

The analysis of these case studies shows that the performance of BPL varies according to the technology used. The companies that conducted mass deployments all used the UPA standard as well as the same product and semiconductor supplier. In addition, the PRIME Alliance has established the ITU G.hn standard (developed by the ITU) as the successor to UPA.

The use cases standardised by the PRIME Alliance demonstrate the potential of BPL technology to significantly improve the management and operation of power grids. From the integration of machine learning algorithms to co-existence with existing technologies, advanced voltage sensing and the use of medium voltage lines for data transmission, BPL offers robust and flexible solutions for today's power sector challenges

Chapter 4. MODEL DEVELOPED

Chapter 4 of the study focuses on the development and analysis of the model used to evaluate the implementation of BPL technology in the low voltage network. This chapter begins with the definition and justification of the project, highlighting the need to overcome the current limitations of the NB-PLC and the importance of digitization in power grids. Next, the hybrid architecture between BPL and PRIME is described, emphasizing how these technologies are integrated to improve the efficiency and responsiveness of the grid.

Subsequently, the chapter explores the technologies employed in the project, providing a detailed technical description of key devices such as the PRIME Base Node, BPL Headend, BPL Splitters, Couplers and Repeaters. These elements are fundamental for the effective implementation of the proposed hybrid solution.

The chapter also discusses the selection of target secondary substations based on specific technical criteria to ensure a successful deployment. The tools used for performance analysis, such as GridValue, Grafana and MapInfo, are described, explaining how the data obtained from these tools are integrated to evaluate technology performance.

Finally, a performance analysis model is presented, including the development of an algorithm for the location of repeaters, and the statistical methods used to calculate network availability and latency averages, as well as the graphical representation of these data. This analysis is essential to validate the implemented technology and to plan future expansions or adjustments in the low voltage network.

4.1 PROJECT DEFINITION

In the current digital era, the demands on power grids are becoming increasingly complex. This project, 'Broadband PLC over the Low Voltage Grid: Pilot Roll-out Results Assessment and Full Forecasting Roll-out,' seeks to address these demands by evaluating and forecasting the deployment of Broadband Powerline Communications (BPL) technology within low voltage grids. This solution aims to improve the efficiency, reliability and responsiveness of power distribution networks.

One of the main drivers for this project is the need to collect more frequent, accurate and higher volume data from smart meters (SM), driven both by stringent regulatory requirements and the growing demand from users to access their consumption data in real time. Currently, smart meter data is collected every 15 minutes, and wait times to access this data online exceed one minute, which is unacceptable for today's digital users. Therefore, there is an urgent need to reduce data collection times to less than 15 minutes to meet regulatory standards and satisfy consumer expectations.

The existing infrastructure, based on PRIME v1.3 technology and narrowband power line communications (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 the BPL technology from secondary substations to meter exchanges and street fuse panels. This transition uses Corinex BPL equipment and ITU G.hn technology in the 2-28 MHz band, using MaxLinear's ITU G.hn MIMO chip, which represents a significant improvement in data rates and real-time monitoring capabilities.

In addition, a critical aspect that this project addresses 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 studied and digitalized. To improve this knowledge, the project has also developed an algorithm that determines the minimum distances between repeaters, starting from the secondary substation, to optimise the deployment of BPL. This development is detailed in Section 4.8.

The main objective of this project is to evaluate the effectiveness of the current BPL technology from Corinex deployed in various secondary substations in the low voltage grid and to determine its suitability for wider deployment. Specific objectives include:

- Assess BPL Technology Performance: Analyse the performance of Corinex BPL equipment under real-world conditions to ensure that it meets the operational needs of the network.
- Development of Network Optimisation Algorithms: Implement and test an algorithm to calculate optimal distances between repeaters to maximise deployment efficiency.
- Explore Alternative Technologies: Consider other BPL technologies if the Corinex solution does not meet the expected functionalities.

This project aims not only to improve real-time data collection and management, but also to deepen the knowledge and optimisation of the low-voltage grid, ensuring a robust, efficient infrastructure that is ready for future challenges. This transformation aligns with the global trend towards smarter and more efficient grids, capable of integrating renewable energy sources and meeting the evolving demands of regulators and consumers.

4.2 PROJECT JUSTIFICATION

The project is fundamental to address contemporary and future challenges in the management and operation of electricity grids. The justification of the project is based on several key pillars that underline its importance and relevance in the current context of the energy sector.

Electricity grids are undergoing a significant transformation driven by electrification, decarbonisation, decentralisation and the need for security. The transition to electric vehicles and other energy-demanding technologies is increasing loads on power grids, which requires an infrastructure capable of efficiently managing these loads. In addition, the integration of renewable energy sources and battery storage systems reduces the carbon footprint, but introduces variability in power generation, requiring advanced monitoring and management solutions to maintain grid stability. Moreover, the decentralisation of energy sources and the emergence of prosumers increase the complexity of the grid, requiring two-way communication and advanced real-time data analysis capabilities.

Broadband over Power Line is positioned as the key enabling technology for the Smart Grid in the low voltage network, significantly enhancing the capabilities of narrowband PLC without adding costs to the current generation of smart meters. While it is possible that the next generation of smart meters, expected within the next 10 to 15 years, may support BPL, the current costs are prohibitive. However, the. ongoing 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. Other technologies, whether due to cost, availability or technical limitations (such as radio in massive underground environments), cannot guarantee ubiquitous deployment of broadband connectivity in LV. This makes BPL a robust and cost-effective solution for managing data demands in a modern power grid, providing several significant advantages:

- It leverages already installed power lines, reducing implementation costs and enabling rapid adoption.
- It offers low latency and high availability, essential for Smart Grid applications that require real-time response.
- It can provide significantly higher bandwidths compared to NB-PLC technologies, reaching data rates of 150 to 250 Mbps.
- It allows energy distribution companies to fully control network communications without relying on third party communication service providers.
- It can interoperate with existing narrowband technologies using IP protocols consistent with UPA or ITU G.hn standards, allowing incremental deployment without the need to completely replace the current infrastructure. This allows DSOs to gradually upgrade their network capacity, integrating new technologies and responding to regulatory and market demands.

However, BPL technology faces several challenges. These include the quality of PLC signal transmission, which varies depending on the type of network (overhead or underground) and the proximity to noise sources. Overhead lines allow better signal propagation due to less interference, while underground networks require the installation of repeater devices at accessible points such as street cabinets or meter rooms.

In addition, low-voltage networks have complex topologies with multiple branches and sub-branches, which can cause signal reflections and affect transmission quality. Solutions to this situation include the use of signal equalisation techniques and low-pass filters, as well as detailed network analysis to identify and mitigate critical reflection points, as discussed previously in Section 3.1.2.

Also challenging is the variability in load and impedance in low-voltage networks, which can cause reflections and loss of signals. The use of advanced filtering technologies and noise mitigation techniques, along with detailed network planning, can help manage these variations and maintain communication quality. Lastly, low-voltage networks are subject to high levels of electrical noise, which can interfere with BPL signals. The implementation of noise-resistant channel coding techniques and the use of repeaters can improve the resilience of the BPL signal.

Another key factor in driving the use of BPL technology is the regulatory framework, along with various directives and mandates that are aimed at promoting digitalization and the integration of advanced technologies.

- E.U. Directive 2019/944 (June 2019): It sets out the framework and objectives for modernising the EU electricity market. This directive obliges utilities to upgrade their networks to accommodate decentralised generation, implement smart metering and demand response systems, and facilitate the integration of distributed energy resources [17].
- EU Action Plan on Digitalizing the Energy System (October 2022): It aims to facilitate the integration of renewables into the EU electricity grid by proposing the

creation of a 'digital twin' of the electricity grid, imposing extensive digitisation requirements. It also aims to establish an international data exchange framework to support the participation of renewable energy sources, ensuring a coordinated and secure approach to grid management in all regions [17].

- FERC Order 2222 (September 2020): This order seeks to promote competition, improve grid reliability and support the growth of clean energy resources in the U.S. By removing barriers and facilitating greater integration of DERs into wholesale electricity markets, this regulation forces utilities to revise their market rules and tariffs to allow DER participation, encouraging greater innovation and efficiency in grid management [17].

The 'Broadband PLC Over Low Voltage Grid' project is key to the modernisation and digitalization of power grids. BPL technology offers a robust, cost-effective and adaptable solution to handle the increasing demands of communication and data management in smart grids. This project not only responds to the immediate needs of modernisation and digitalization, but also lays the foundation for a more resilient, secure and efficient electricity grid, capable of meeting the energy and climate challenges of the future. Adherence to regulations such as EU Directive 2019/944, the EU Energy System Digitisation Action Plan and FERC Order 2222 ensures that the project is not only relevant, but also essential for the evolution and sustainability of modern power grids.

4.3 DESCRIPTION OF THE MODEL

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.

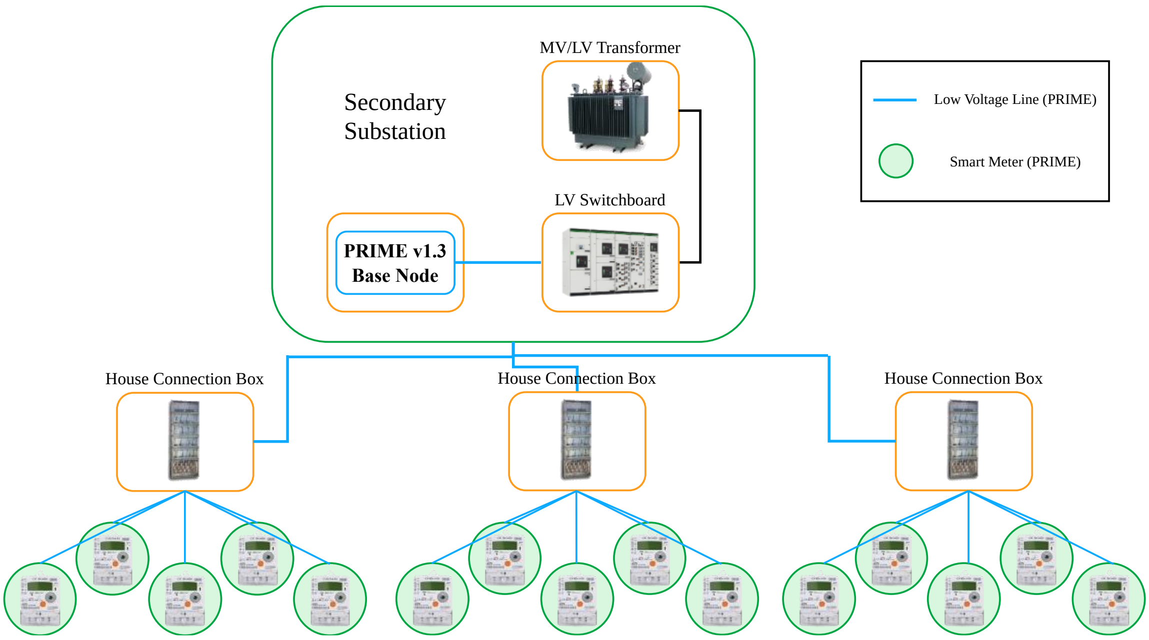


Figure 16. Actual Solution (100% PRIME v1.3).

The current model, which is represented in Figure 16, 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 17, 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.

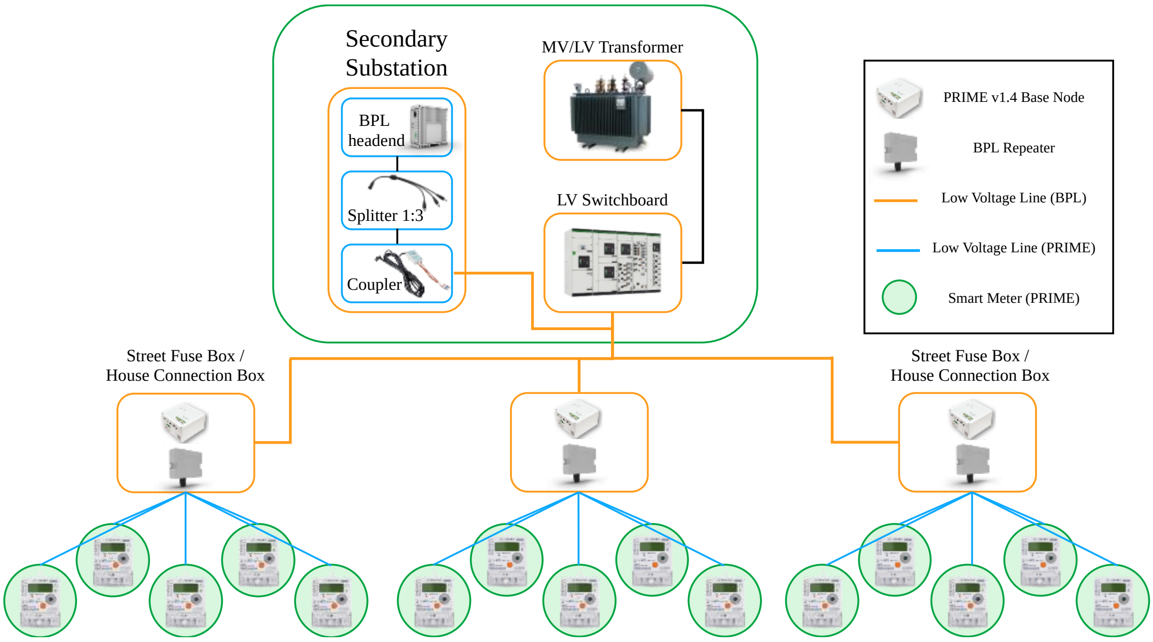


Figure 17. Hybrid Solution (BPL + PRIME v1.4).

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.

4.4 TECHNOLOGY EMPLOYED

This section describes in detail the key technologies employed in the current PRIME v1.3 architecture and in the hybrid low voltage network architecture combining BPL and PRIME v1.4. The main components and their role within this advanced infrastructure will be discussed, from the communication devices such as the PRIME v1.3m PRIME v1.4 Base Node to the essential BPL system elements such as the coupler and the repeater.

4.4.1 BASE NODE PRIME V1.3

The Base Node PRIME v1.3 is the central device in the NB-PLC network, which acts as the base node within a secondary substation (SS). This device manages the communication between the Smart Meters and the grid infrastructure. It operates using the PRIME v1.3 standard, which operates in the 42 kHz to 89 kHz band, and coordinates data transmission using a time division multiple access (TDMA) scheme. The capacity of the Base Node PRIME v1.3 is limited to an effective data rate of up to 21 kbps under saturated network conditions. Despite its robustness in noisy environments, its data handling capability is limited, which has led to the need for an upgrade to more advanced versions such as PRIME v1.4 [23].

4.4.2 BASE NODE PRIME V1.4

The Base Node PRIME v1.4 improves significantly over its predecessor by operating in a wider frequency band of up to 500 kHz, which allows for a much higher data rate of up to 1 Mbps. This device is designed to improve efficiency and reduce latency in the network, as it can handle smaller networks with fewer counters per node, allowing for more direct and faster communication with each counter. In addition, PRIME v1.4 incorporates adaptive modulation schemes and robust transmission modes, increasing resilience to interference and enabling more efficient management of data traffic [24].

The transition to PRIME v1.4 does not require complete replacement of the existing infrastructure, as PRIME v1.3 devices can co-exist with the new PRIME v1.4 devices. This facilitates a progressive migration and allows existing networks to benefit from the performance improvements of PRIME v1.4 without significant service interruptions.

4.4.3 BPL HEADEND

The BPL Headend is the central core of the BPL network, responsible for the management and collection of data from multiple BPL repeaters and nodes distributed in the low voltage network. This device uses ITU G.hn MIMO technology, operating in a frequency range of 2 to 50 MHz, and is capable of handling data rates of up to 1 Gbps under optimal conditions. The Headend is designed to handle large volumes of data traffic, prioritising the transmission of critical information and ensuring low latency communication between nodes. In addition, it implements advanced security protocols that ensure the integrity and confidentiality of data transmitted over the power grid [25].

Figure 18. BPL Headend [25].

4.4.4 SPLITTER AND LV COUPLER

The splitter divides the BPL signal into multiple outputs, allowing the signal to be injected into various phases of the low voltage network. The splitter can handle 1:2 or 1:3 configurations, depending on the network design, and is essential for evenly distributing the BPL signal along the power lines [3].

The coupler used in Corinex's BPL technology allows the BPL signal to be transmitted efficiently over power lines, ensuring minimal signal loss and high data transmission efficiency. It operates in a range of 2 to 50 MHz, allowing it to support high-speed data transmission without significant interference. It can inject the BPL signal into multiple phases of the low-voltage network using a specialised design that minimises signal degradation. Moreover, it is designed to withstand the harsh environmental conditions typical of electrical installations, including temperature variations and exposure to external elements. In addition, it includes protection mechanisms against surges and other electrical anomalies, ensuring the durability and reliability of the device in industrial environments [26].

Figure 19. BPL LV Coupler [26].

4.4.5 BPL REPEATER

The Corinex BPL repeater acts as a signal regenerator in the low voltage network, allowing the BPL signal coverage to be extended without significant loss of quality. This device is crucial in large power grids, where signal attenuation could compromise the quality of data transmission. The repeater operates in a range of 2 to 50 MHz, allowing it to maintain compatibility with the BPL network and support high-speed data transmission. It uses ITU G.hn MIMO technology, which improves spectral efficiency and allows multiple signals to be transmitted simultaneously over the same power lines, thus maximising the network's transmission capacity. It not only amplifies the signal, but also cleans it from interference and distortion, ensuring that the data reaches its destination with high fidelity. They are strategically installed in the network, at points such as SFBs or low voltage lines where the signal needs to be regenerated to maintain its integrity. Their robust design allows them to be installed in a variety of environments, including exposed areas and underground locations [27].

Figure 20. BPL Repeater [27].

4.5 TARGET SECONDARY SUBSTATIONS

In the context of the modernisation and expansion of BPL technology in the low voltage grid, the selection of secondary substations for field trials is a critical process that must be approached with technical and strategic rigour. The objective of this section is to provide a description of the criteria and processes that were used in the thesis of J. Berzal Hernández, "Broadband PLC Deployment in the Low Voltage Grid" (Universidad Pontificia de Comillas, Madrid. August 2022), to identify and prioritise secondary substations that are considered suitable for BPL deployment.

The secondary substation selection process is based on a detailed analysis of the technical requirements necessary for the deployment of BPL in the low-voltage network. As illustrated in Figure 21, the procedure starts with the identification of SSs that meet a set of predefined criteria, followed by a detailed assessment that assigns scores to eligible SSs according to their level of applicability. Finally, the 324 most suitable SSs are selected for field trials [3].

Figure 21. Target SS selection [28].

Of the 103,387 existing secondary substations in i-DE's network, only 6,260 have been identified as eligible for BPL deployment in the low-voltage grid, representing approximately 6% of the total number of SSs. These results can be observed graphically in Figure 22.

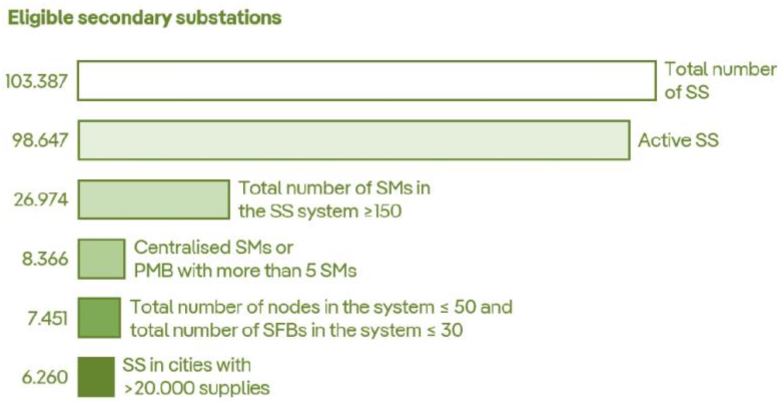


Figure 22. Eligible Secondary Substations for field trials [3].

It is observed that as main criteria, priority is given to SSs with a high number of connected smart meters, specifically those with more than 150 SMs, choosing SMs centralisations with more than 5 SMs. Following this, SSs with a few nodes in the system less than or equal to 50 and a total number of SFBs less than or equal to 30 are favoured, indicating a more manageable and less complex network topology. SSs located in cities with more than 20,000 supplies are prioritised, as these areas represent a greater impact in terms of energy efficiency and customer service.

After identifying the eligible SSs, a ranking process is carried out in which SSs are evaluated on several additional parameters. The determining factors for the final selection of the 324 SSs include: high SMs density, high percentage of SFBs in their locations, lower number of PMBs and low voltage lines, and the SS where the SFBs are geographically closer to the SS [3].

The choice of BPL-free SS over its medium voltage network is key to avoid interference and ensure a controlled test environment. In addition, preference is given to SS with more than 50 non-securable SM, allowing these devices to be retrofitted with PRIME v1.4 compliant technology. Finally, SS are selected in large locations and close enough to each other to allow for simultaneous deployment, maximising project efficiency and facilitating operational management during field trials [3].

4.6 TOOLS FOR PERFORMANCE ANALYSIS

Following the selection of secondary substations according to the criteria described in Section 4.5, Corinex's BPL technology, which follows the model described in Section 4.3, has been deployed in 70 SSs out of the 324 selected for field testing. To analyse the performance and operation of this technology, several tools are used that were previously presented in Section 1.5. In this section, their operation and use as applied to the project will be discussed in more detail.

4.6.1 MAPINFO

MapInfo Professional 12.0 is the geographic information systems (GIS) software used by Iberdrola to manage and analyse the telecommunications and electricity infrastructures within its distribution area in Spain. This software allows Iberdrola to visualise and graphically manage all telecommunications assets through the SICOID tool (Iberdrola's Communications Information System).

SICOID is Iberdrola's customization of the General Electric GIS platform, Smallworld, specifically designed to represent and manage Iberdrola's telecommunications networks, including technologies such as SDH, DWDM, MPLS, fibre optics and radio, among others. MapInfo, on the other hand, is a more general-purpose GIS that uses the information obtained from SICOID, along with additional data sources. The strength of MapInfo lies in its ability to be manipulated by non-specialist users. In addition, SICOID is combined with SIGRID, another GIS system that allows the visualisation of power grids, integrating both the telecommunications infrastructure and the power grid in a single platform. This capability is crucial for the BPL-LV project, as it allows a detailed visualisation of the low-voltage network, both in electrical and telecommunications terms.

The data provided by MapInfo consists of, for each SFB of the analysed SS, the line on which it is located, the SFB or SS to which it is connected (upstream), the distance to the SS, the distance to the SFB connected upstream and the SFB model.

The use of MapInfo in this project is not limited to network visualisation. One of the most important functionalities is the possibility to relate BPL technology performance data to the physical infrastructure represented in the GIS. For example, with the help of the data provided by MapInfo, it is possible to analyse whether the deployment of BPL technology is effective by providing the distances between the SFBs and the corresponding secondary substation. This information is key to understanding the limitations and performance of the technology depending on the network topology.

In addition, within the framework of this project, an algorithm has been developed so that, with the help of MapInfo, the knowledge of the low voltage network can be deepened. This algorithm is designed to determine the minimum distances between one repeater and the next, starting from the secondary substation. This development is discussed in detail in Section 4.8.

4.6.2 GRAFANA

Grafana is a robust and versatile software designed for the visualisation and analysis of data collected from equipment deployed on the network. Its ability to transform raw data into meaningful graphs and charts makes it a key tool for BPL-LV network performance monitoring.

Grafana allows the customisation of dashboards, which provide a detailed representation of equipment performance. In addition, alerts and notifications can be set up to detect potential failures in the BPL-LV deployment. This flexibility in configuration facilitates early identification of problems and enables rapid intervention.

In the context of this project, Grafana was used to perform a ping analysis on the BPL-LV network, which involved assessing connectivity and latency between devices. Ping is a tool based on the Internet Control Message Protocol (ICMP), which is essential for diagnosing the status of the network and ensuring that devices are communicating correctly. ICMP is a network protocol mainly used by network operating systems to send error messages, but it is also crucial in connectivity tests such as ping. When a ping is executed, the system sends an ICMP Echo Request message to a target device. If the device is online and reachable, it responds with an ICMP Echo Reply message.

To obtain the relevant data from Grafana, it is first necessary to establish a period for data collection, which in this case is 13-20 May. It is also required to determine an interval, which indicates the frequency with which the data is collected, in this case 5 minutes. In addition, it is needed to select the secondary substation on which the study is going to be carried out. In this way, 4 graphs and thus 4 data sets are obtained.

The first two graphs provided by Grafana represent the percentage of packets lost, and the average ping for each line in the secondary substation. These two data sets are not discussed further, as they were not used to obtain the project results.

Moreover, data is obtained on the percentage of packets lost by each BPL equipment. Packet loss for each BPL equipment occurs when one or more data packets do not reach their destination. In a ping analysis, this is reflected as the lack of an echo response, which may indicate connectivity problems, network congestion or hardware failure. The percentage of lost packets is a critical metric for assessing network reliability. This information provides insight into the availability of each BPL equipment, since the higher the percentage of lost packets, the lower the availability of that equipment.

The last graph shows the ping for each BPL equipment, which provides information on the latency with which each repeater connected to the substation's master equipment operates. To achieve latency display, Round-Trip Time (RTT) is used, which measures the time it takes for a data packet to travel from source to destination and back to the source. RTT, or latency, is a key metric for assessing network speed. A lower RTT indicates a faster and more efficient connection.

4.6.3 GRIDVALUE

Corinex GridValue is an advanced grid management solution designed to monitor and analyse data in the low voltage grid. As an integral part of Corinex's BPL solution, GridValue offers near real-time detection and management capabilities, enabling utilities to optimise the operation of their networks. In its current state, GridValue's data representation is via a dashboard that allows several key aspects to be observed: device availability, network profile analysis, PHY rate analysis., the grid topology and an inventory of the devices.

Firstly, the device availability dashboard allows the selection of a specific secondary substation to obtain data on its performance in terms of availability. In this project, a period of one week, from 13 to 20 May 2024, was selected to ensure time consistency in data collection. Although it is possible to select shorter or longer periods, up to 30 days, the choice of a fixed period facilitates the comparative analysis. From this selection, the dashboard allows data to be extracted in Excel format, including data transmission and reception rate, signal-to-noise ratio (SNR) and bit error rate (BER). In addition, it displays an availability graph indicating when the selected device is active (1) or inactive (0), along with a cumulative availability graph.

The profile analysis dashboard shows the behaviour of phase voltages, with a panel that triggers alarms if ideal voltage thresholds are exceeded that could affect the equipment. However, this dashboard was not used in the project, so its content is not explored in depth.

Finally, the PHY rate analysis dashboard was the main tool used to obtain the project results. For this purpose, the period from 13 to 20 May 2024 was again selected. Through this dashboard, an Excel file was obtained for each SFB of the secondary substation studied, allowing to observe the data transmission and reception speeds, the master to which it was connected in each data acquisition, as well as the phase voltages. Although GridValue allows a graph of the evolution of the data rates during the selected period to be displayed, it is presented separately for each SFB.

In addition, GridValue includes a section called Topology, which allows you to visually and easily observe the configuration of the selected secondary substation. This section shows schematically the master device together with its proxy, the connected repeaters and data rates, as well as the active alarms and the hopping count. This visual representation makes it easier to understand the network structure and to quickly identify possible problems.

Although GridValue provided valuable insights through the PHY rate analysis dashboard, the need to observe the joint behaviour of all SFBs led to analyse the data globally in an Excel sheet created specifically for this purpose, which will be described in detail in Section 4.7.

4.7 RESULTS ANALYSIS MODEL

This section describes the analysis model used to evaluate the results obtained from the Grafana, GridValue and MapInfo tools. With the data collected, a structured approach has been developed to represent and analyse the information of each secondary substation with a clear and visual approach.

4.7.1 DATA INTEGRATION IN EXCEL

For each SS, an Excel workbook has been created to visualize the data in an organized manner. This data includes critical information on network availability, latency, and transmit and receive speeds.

- Network availability: Using Grafana data, the availability of each repeater in the SFBs was recorded over a one-week period, with data collected every 5 minutes. This data is given as the percentage of lost packets, which indicates the fraction of data packets that do not reach their destination during transmission. A high percentage of lost packets suggests connectivity problems or network interference. Availability is calculated from the percentage of lost packets using the formula:

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

  This value represents the proportion of the time during which the network was effectively operational, i.e. when most of the data was transmitted correctly. To simplify the analysis, an average availability was calculated for each SS, both directly and weighted according to the number of smart meters connected to each repeater.

- Latency: Latency is measured in milliseconds using the ping analysis provided by Grafana. As with availability, an average latency was calculated for each SS, considering the average of all repeaters in each SFB.
- Data rates: The data obtained from GridValue was used to analyse the data transmission and reception speeds of each repeater individually.

To perform the average availability calculation, for each 5-minute interval, the availability of all repeaters within the SFBs connected to the substation is taken and their simple mean is calculated. This arithmetic average provides an overview of how available the SS was during each interval. To represent it mathematically, the average availability is defined as:

$$Average\ Availability = \frac{1}{N} \cdot \sum_{i=1}^{N} A_i$$

where A_i represents the availability of the i-th repeater at a given time, and N is the total number of repeaters in the SS.

To get a more accurate view of the availability impact on the network, a weighted average is calculated, where the importance of each repeater is based on the number of smart meters connected to it. This ensures that repeaters managing more SMs have a greater impact on the overall SS availability measure. The weighted average availability is defined as:

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

where w_i represents the number of SMs connected to the i-th repeater. This approach allows to evaluate how the availability of each repeater affects the overall availability of the SS, considering the distribution of SMs.

4.7.2 GRAPHIC REPRESENTATION IN EXCEL

This section explains the two main graphs generated to analyse the results of the network in each secondary substation using the collected data.

a. Complete SS Graph

This graph collectively shows three important metrics for the entire SS:

- Average Availability: This metric reflects the average availability of all SS repeaters in 5-minute intervals during a week. It allows observing how the overall availability of the SS behaves over time.
- Weighted Average Availability: In addition to the simple average, a weighted average is calculated to consider the number of smart meters connected to each

repeater. This metric is crucial to identify how repeaters with more connections impact overall availability.

- Average Ping: Average latency (RTT) is plotted on the same graph, making it easy to compare latency and availability. This allows to understand how variations in latency may be correlated with changes in availability.

These three metrics are presented in a single graph so that, over the course of the week, it can be clearly observed how availability and latency interact across the SS. The joint representation allows to detect patterns and correlations that might not be evident if analysed separately.

b. Individual Repeater Graph

For each individual repeater within the SS, a specific graph is generated showing:

- Data Rates: This graph presents the data transmission and reception rates of the repeater throughout the week. This data allows to evaluate the repeater's performance in terms of data capacity.
- Repeater Availability: Next to the speeds, the repeater availability is displayed, but with the data grouped in one-hour periods. Grouping the data by hour makes it easier to visualize and to identify extended periods of downtime or performance problems.

Combining these metrics into a single graph per repeater allows not only to evaluate its performance in terms of speed, but also to observe how availability varies over time and how it may be related to transmit and receive speeds.

The Excel graphs are designed to provide a comprehensive and detailed view of network performance, both at the overall SS level and at the individual repeater level. This facilitates deeper analysis and allows for the identification of specific areas for improvement or potential problems in the BPL infrastructure.

4.7.3 MAPINFO INFORMATION

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

4.8 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 digitised 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 optimise the deployment of BPL. This development is discussed in detail in this section.

To start with this process, the data provided by MapInfo are the connections between SFBs and bifurcations (BF), with the distances between them. Bifurcations are considered to be points that are electrically equal, where repeaters cannot be placed.

4.8.1 STEP 1: CLUSTER IDENTIFICATION

A definition is needed of Cluster, which is the set of SSs and/or SFBs linked together directly, or by means of bifurcations. First, the LV line is traced from the SS onwards, downstream. Arrays are created for each cluster. It must be considered that in the union between elements (SS, SFB or BF), if two elements (SS and/or SFB) are directly joined, they form a cluster. If between SSs and SFBs there are BFs, all the elements interconnected by the BF, and those that are connected, are of the same cluster.

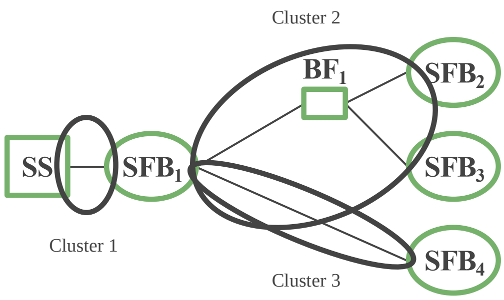


Figure 23. Example of Low Voltage Line with Identified Clusters.

Figure 23 shows the identification of the different clusters in the low voltage line used as an example. On the other hand, **Error! Reference source not found.** shows the arrays that w ould have to be created for this particular LV line.

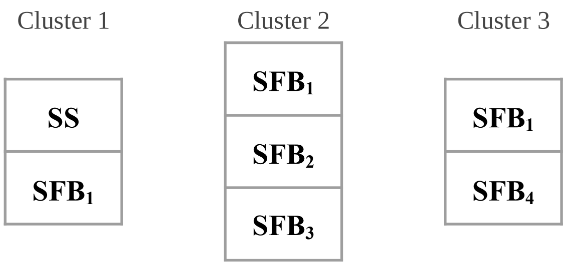


Figure 24. One array per cluster.

4.8.2 STEP 2: CLUSTER CONNECTION

For the achievement of the second step, it is necessary to first go through the clusters starting from Cluster 1, which is the one that always contains the SS. From each element that is not the SS of Cluster 1, the anchor point ("pointer") to the rest of the arrays is sought. If a cluster element does not find its anchor point to another cluster, it determines that at that point is the "end" of the line, or one of its ends.

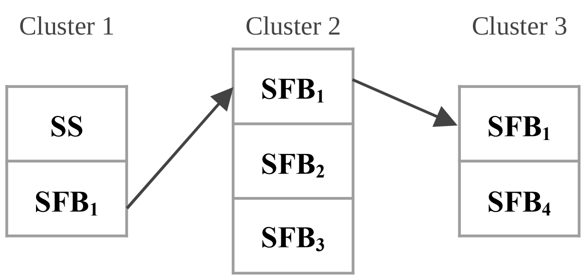


Figure 25. Pointer Designation.

4.8.3 STEP 3: CALCULATION OF DISTANCES PER CLUSTER

The objective of this step is to determine, within each cluster, the distances of all SFBs from all SFBs. An example cluster is shown in Figure 26 to illustrate the process.

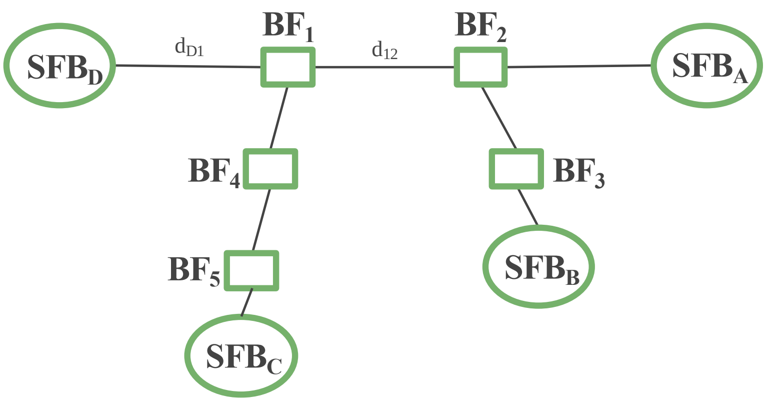


Figure 26. Cluster example.

Firstly, it is necessary to determine 3 groups of distances that can exist: a) Distance between SFBs: S-S, b) Distance between SFBs and BFs: S-B, c) Distance between BFs: B-B. To observe the process undergone by the distances, which are held as data, these three groups of distances will be presented in table form. To designate the distances, it will be considered that, if it is between two bifurcations, for example BF_1 and BF_2, the distance will be d_{12}, while if the distance is between an SFB and a BF, such as SFB_D and BF_1, the distance will be d_{D1}. Table 4 shows the distances obtained from MapInfo as initial data.

(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 4. Initial Baseline Data.

After the previous step, it is necessary to make the substitution in column (c) of the bifurcations of (b) of Table 4 that appear only once in (c). With this, the objective is set to find the BF that is the centre of the star, i.e., the central point, being in this case B1. The substitution made is as follows:

$$B_1 - B_2 = d_{12} \rightarrow B_1 - S_A = d_{12} + d_{A2}(B_2 - S_A)$$

$$B_1 - B_3 = d_{13} \rightarrow B_1 - S_B = d_{13} + d_{B3}(B_3 - S_B)$$

$$B_4 - B_5 = d_{45} \rightarrow B_4 - S_C = d_{45} + d_{C5}(B_5 - S_C)$$

Thus, eliminating the distances already used, updating Table 4 yields the following:

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

Table 5. First Iteration.

Subsequently, it is necessary to rearrange the columns according to the corresponding distances, as shown in Table 6.

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

Table 6. Distances reorganization.

From this point on, the iterative process is repeated. In this case, the common BF in all the relations (BF_1) must be selected and the rest of the BFs must be substituted so that BF_1 is the only one that appears. In this way, the distance between each SFB and the central BF is obtained. The result obtained is shown in Table 7.

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

Table 7. Distance between each SFB and the central BF.

Thus, the common central bifurcation must be replaced to find the distances between the SFBs themselves:

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

Table 8. Final distances result.

Finally, 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:

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

4.8.4 STEP 4: MINIMUM DISTANCE SELECTION

Finally, it is necessary to determine the minimum distances starting from the SS. For this, step 2 is used to determine the connection between clusters. Within each cluster, the next element to be chosen is the one with the shortest distance to the previous one, always starting from Cluster 1.

When the cluster consists of only two elements, the process is trivial. However, if there are more than two elements, if the chosen element is not connected outside the cluster, processing is continued to search for the next element within the cluster. Moreover, if the chosen element is connected outside the cluster, it is necessary to reanalyse those elements that the algorithm has not passed through.

After the development of this methodology, by incorporating this algorithm within MapInfo, an optimized solution for the location of BPL repeaters is provided, ensuring maximum coverage and signal quality with the minimum number of repeaters required. This algorithm not only helps to efficiently deploy repeaters in the LV network, but also contributes to improve the knowledge about the network topology. The implementation of this algorithm is a crucial step in overcoming current limitations and ensuring robust and reliable performance in the BPL network, especially in areas where the electrical infrastructure is complex and understudied.

Chapter 5. RESULTS OF THE RESEARCH

This chapter will provide an analysis of the results obtained after the deployment of hybrid BPL and PRIME v1.4 technology in 68 secondary substations. The main objective is to evaluate the effectiveness and performance of the implemented system, identifying behavioural patterns and possible areas for improvement.

5.1 PERFORMANCE OVERVIEW

This section presents a detailed analysis of the performance of 68 secondary substations that have been evaluated after the implementation of the hybrid BPL and PRIME v1.4 technology. To facilitate the understanding of the data, a table has been generated that includes three key metrics for each SS: average availability, weighted average availability, and average latency (ping), provided by Grafana. The table is visually organized using a conditional colour format, where, in the case of availability, the highest values are shown in green, intermediate values in yellow, and the lowest values in red, while the reverse is true for latency. This format helps to identify patterns and extremes quickly, although it is not directly stated that a green colour implies excellent performance or a red colour poor performance, due to the lack of clearly defined thresholds for these metrics. The table is included in Annex I, to facilitate its visualization.

5.1.1 METRICS DISPLAYED

The average availability of the entire SS is shown first, representing the average percentage of time the SS was operational without packet loss during the period analysed. This metric was calculated by taking the average of the mean values obtained in section 4.7.1, over a period of one week. Although this metric is an indicator of how long the network infrastructure has been functional, without a defined threshold it is not possible to accurately determine whether close to 100% availability is excellent or merely acceptable.

The weighted average availability of the SS is similar to the average availability but adjusted by the number of smart meters connected to each repeater. As with the mean, this value was obtained by calculating the average of the weighted mean values obtained in section 4.7.1. This allows to assess the impact of the most critical repeaters on the overall availability of the SS. Again, although values close to 100% could be interpreted as positive, the lack of standard criteria for these results implies that further analysis is required before definitive statements can be made.

Latency, measured in milliseconds (ms), indicates the time it takes for a data packet to make a round trip between two points in the network. A lower latency value generally suggests a faster network. However, it is important to note that end-to-end latency measurements are not always relevant in this context, as latency has so far been found to be more associated with WAN connectivity (e.g. 2G) and less with the number of BPL repeaters. Therefore, although latency is presented in the table, conclusions about its impact on performance should be considered with caution.

5.1.2 Table Analysis

The table presents significant variability between substations, both in terms of availability and latency. However, due to the lack of established criteria for determining what constitutes either good or poor performance, the discussion focuses on identifying general patterns and extremes, rather than categorically assessing the quality of performance.

- Substations with High Availability Values: Some substations such as SS_{16}, SS_{39}, SS_{44}, and S_{68} show availability values close to 100% in both simple and weighted averages, accompanied by relatively low latencies, as it can be observed in Figure 27. These cases can be considered indicators of stable operation. However, it is important to note that, without a clear threshold, it cannot be categorically stated that these SSs are operating "excellently". Rather, these SSs appear to be operating within what could be a positive range, although further testing would be necessary to confirm this.

Figure 27. 100% Availability substations.

- Substations with Significant Differences between Average and Weighted Average: It is important to note the SS where there is a notable difference between average availability and weighted average availability, as in the cases of SS_{25}, SS_{32}, and SS_{56}. These differences suggest that certain repeaters, especially those with a higher number of connected smart meters, have a more significant impact on overall SS availability. A significantly lower weighted average availability value, such as in SS_{25}, which has an average availability of 55%, but its weighted availability drops to 33%, indicates that the most critical repeaters in terms of SM connectivity are experiencing more problems than average, which could be a key area of focus for improving performance. These results are represented in Figure 28.

Figure 28. SS Difference between Average and Weighted Average Availability.

- Substations with Low Availability and Low Latency (SS24, SS56): Substations such as SS_{24} and SS_{54} show low availability (55% and 26%, respectively), but surprisingly have low latency (123.29 ms and 47.21 ms). This could suggest that these SSs are experiencing frequent network outages, but when the network is operational, it operates efficiently. The combination of low availability and low latency is unusual and could indicate intermittent problems that should be investigated further. 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.

The construction of this table facilitates the identification of substations that exhibit good overall performance and those that require attention. In section 5.3, three representative SS will be selected - one with "high", one with "medium" and one with "low" availability values - for a more detailed analysis of their performance, which will help to better contextualize the results and understand the underlying factors that might be influencing these metrics.

5.2 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. This analysis allows the identification of specific patterns or causes behind the observed performance and helps to formulate recommendations for future implementations.

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)
SS20	100%	100%	64.39
SS52	69%	65%	570.41
SS67	26%	14%	43.38

Table 9. Secondary Substations to be studied.

In the availability and ping graphs provided in Sections 5.3.1, 5.3.2 and 5.3.3, 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.

5.2.1 SS_{20} - HIGH AVAILABILITY AND LOW LATENCY

The SS20 substation is notable for its high availability and low latency, making it an ideal case study for understanding the conditions that favour optimal performance. This analysis will focus on interpreting the graphs and tables provided to identify patterns, possible causes of problems and relationships between the different variables, as well as the variation observed in the graphs. Below is a summary table with the topology of this SS provided by MapInfo.

Line number	Previous SFB code	SFB code	Previous SFB distance	Number of SM
1	SS	SFB1	64	17
2	SS	SFB2	30	10
3	SS	SFB3	45	9
4	SS	SFB4	12	18
5	SS	SFB5	57	13

Table 10. Topological information for SS20.

a. Plot of Average and Weighted Average Availability along with Latency.

In the case of this substation, both the average availability and the weighted average availability remain consistently high, close to 100%, throughout the period analysed. This stability is a clear indication that the network in this substation operates without significant interruptions. It is remarkable that the weighted average closely follows the simple average, indicating that there is no uneven impact on availability due to the number of SMs connected to the different repeaters. This suggests a uniform distribution of workload among the repeaters.

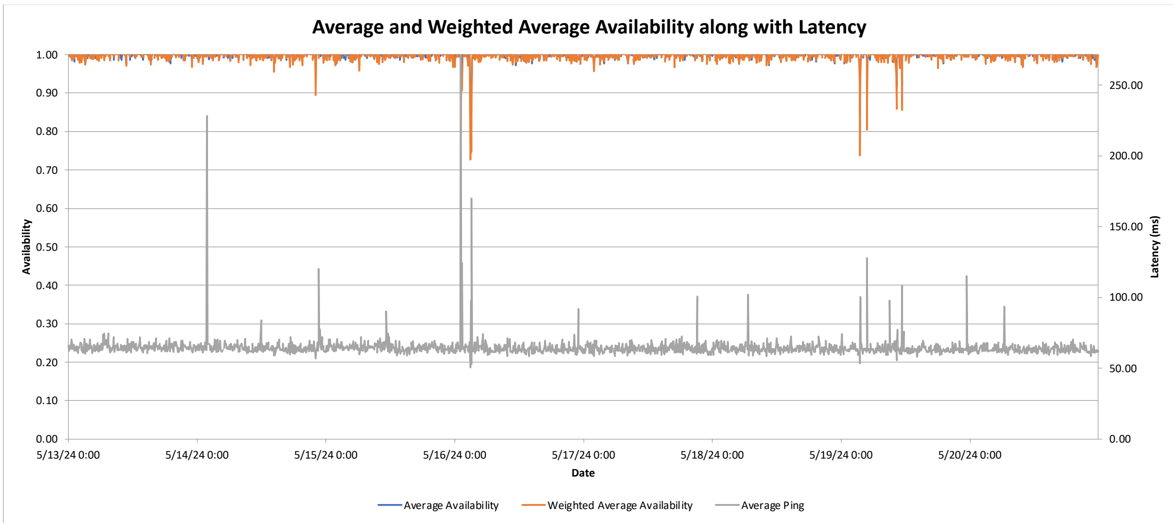


Figure 29. Average and Availability along with Latency SS20.

Average latency remains at low and stable levels, around 60 ms, with some isolated peaks 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 time. The observed peaks, although isolated, may 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.

c. Transmission Rates and Availability Graphs per repeater in SFB.

The individual graphs per SFB provide additional details on the performance of each repeater in terms of transmission rates and availability:

SFB_1 is located at 64 m from the SS and has 17 SM connected, as can be observed in the Table 10. Transmit and receive rates are consistently high, with slight variability that does not appear to affect the high availability of the repeater. Availability remains close to 100% throughout the period, suggesting that the relatively long distance is not significantly affecting performance.

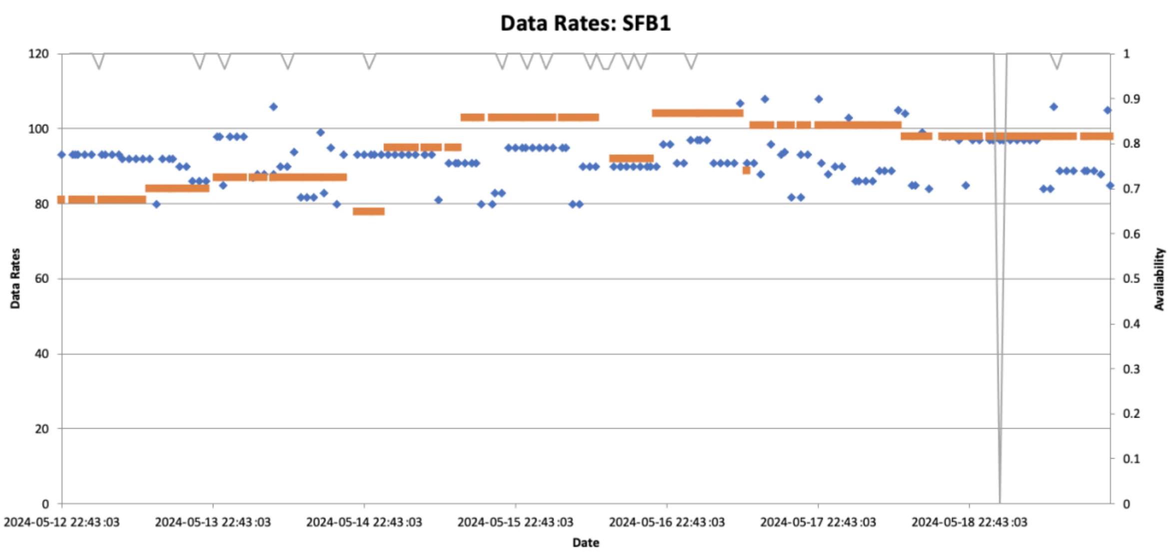


Figure 30. Data Rates SFB1 SS20.

SFB_2 is located at 30 m from the SS and has 10 SM connected, as can be observed in the Table 10. This repeater, with a medium distance and a moderate number of connected SMs, shows an equally stable transmission and reception rate, with availability remaining high.

No significant drops (note that the availability axis shows 0.965, not 0, as the lower limit) in availability, indicating reliable operation.

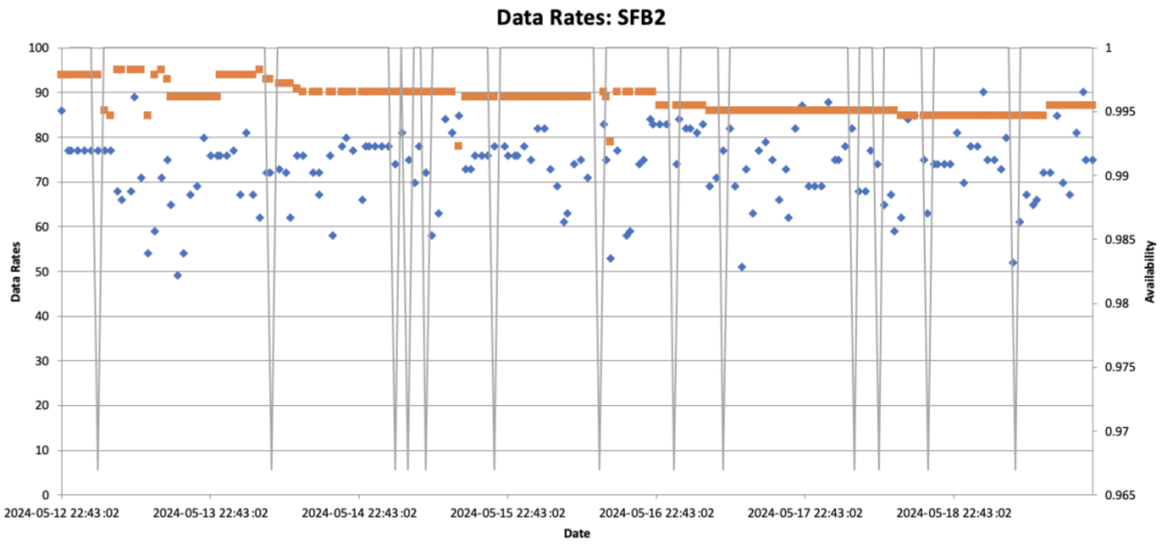


Figure 31. Data Rates SFB2 SS20.

SFB3 is located at 45 m from the SS and has 9 SM connected, as can be observed in the Table 10. Like previous repeaters, SFB3 maintains stable transmission rates, showing a slightly higher variability in reception speed, and high availability. Although transmission rates show slight variability, there does not appear to be a noticeable impact on the overall stability of the repeater.

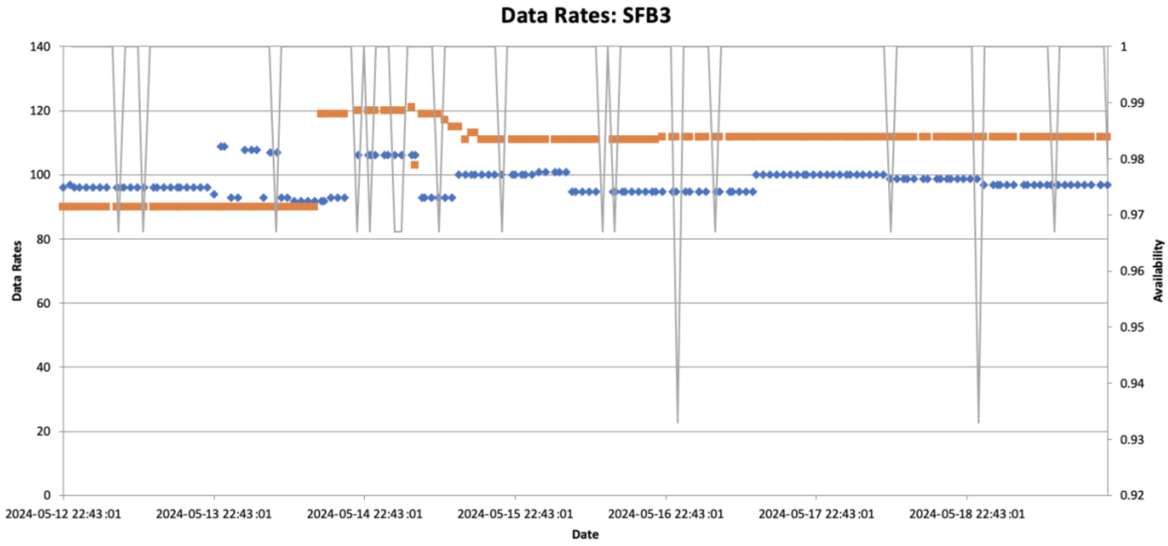


Figure 32. Data Rates SFB3 SS20.

SFB4 is located at 12 m from the SS and has 18 SM connected, as can be observed in the Table 10. Despite having the highest number of SMs in the SS, SFB4 maintains a high and stable transmission rate, with equally high availability. The proximity to the SS could be contributing to the consistency in throughput, although the relatively high number of SMs does not seem to affect availability.

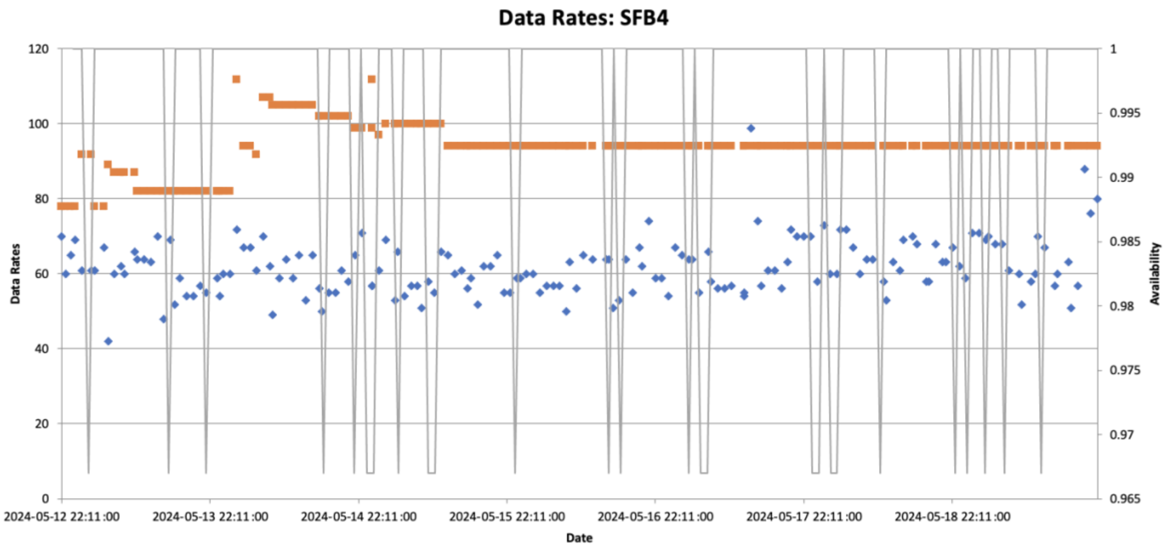


Figure 33. Data Rates SFB4 SS20.

SFB_5 is located at 57 m from the SS and has 13 SM connected, as can be observed in the Table 10. Although it features one of the longest distances, SFB_5 continues to show stable performance in terms of transmission rates and availability. The near 100% availability suggests that the repeater is efficiently handling the load, despite the distance.

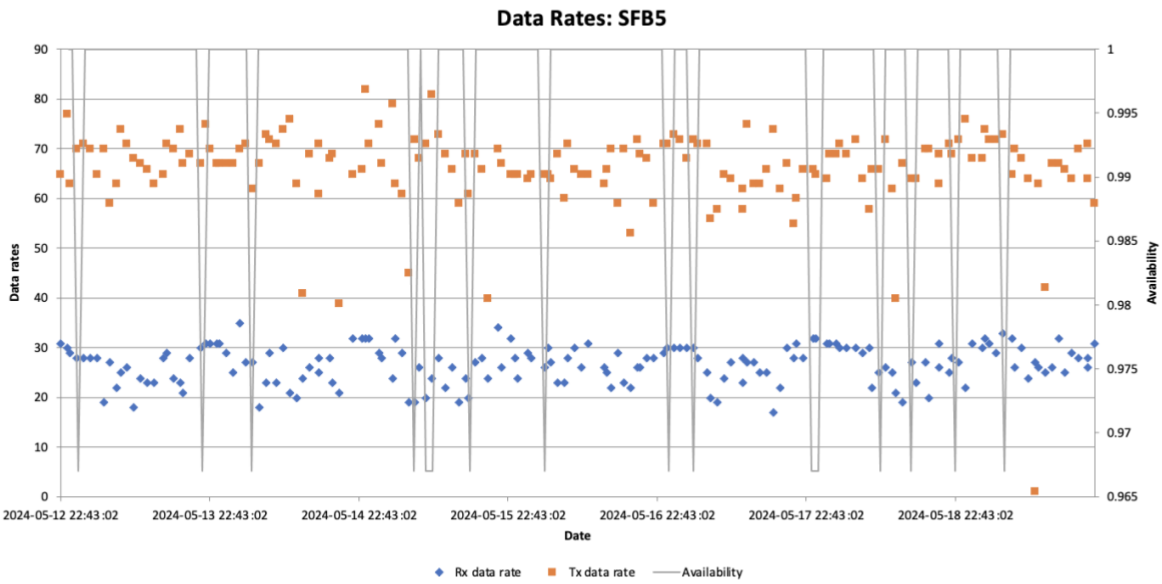


Figure 34. Data Rates SFB5 SS20.

Based on the data provided in Table 10, distance does not seem to play a negative role in availability. The repeaters, even those at longer distances such as SFB1 and SFB5, show high availability, which could indicate that the infrastructure at SS_{20} is robust and capable of maintaining signal integrity over long distances. Although some repeaters have a larger number of connected SMs, this does not seem to negatively affect availability or stability of transmission rates. This balance suggests efficient load sharing between repeaters, contributing to optimal substation performance.

The SS_{20} substation shows high availability and low latency, suggesting that the infrastructure and workload distribution at this substation are optimized. The consistency in transmission rates and availability across all SFBs indicates that the network at SS_{20} is robust, with good management of distances and SM load. Isolated spikes in latency do not appear to have a significant impact on overall performance.

5.2.2 SS_{52} - MEDIUM AVAILABILITY AND MEDIUM LATENCY

Substation SS_{52} represents an intermediate case with medium availability and medium latency. This detailed analysis of the graphs and tables provided will focus on identifying patterns, understanding the causes of the observed problems, and determining how SM topology and loading affect performance. Below is a summary table with the topology of this SS provided by MapInfo.

Line number	Previous SFB code	SFB code	Previous SFB distance	Number of SM
1	SS	SFB1	9	20
2	SS	SFB2	46	18
2	SFB2	SFB3	14	1
2	SFB3	SFB4	16	19
2	SFB4	SFB5	15	19
2	SFB5	SFB6	10	1
2	SFB6	SFB7	0	1
3	SS	SFB8	18	20
3	SFB8	SFB9	34	21
3	SFB9	SFB10	16	20
4	SS	SFB11	82	20
4	SFB11	SFB12	23	19
5	SS	SFB13	31	18
7	SS	SFB14	5	0

Table 11. Topological information for SS52.

a. Plot of Average and Weighted Average Availability along with Latency.

In the case of this substation, the average and weighted average availability show fluctuating values ranging from 50% to 90%. This variability suggests that the network at SS_{52} is not operating optimally and suffers from instability. It is important to note that the weighted average is generally lower than the simple average. This indicates that repeaters with more SMs connected have lower performance in terms of availability, suggesting that the more heavily loaded areas are negatively affecting the overall substation result. Peaks and drops in availability may be related to specific repeater problems or fluctuations in network load.

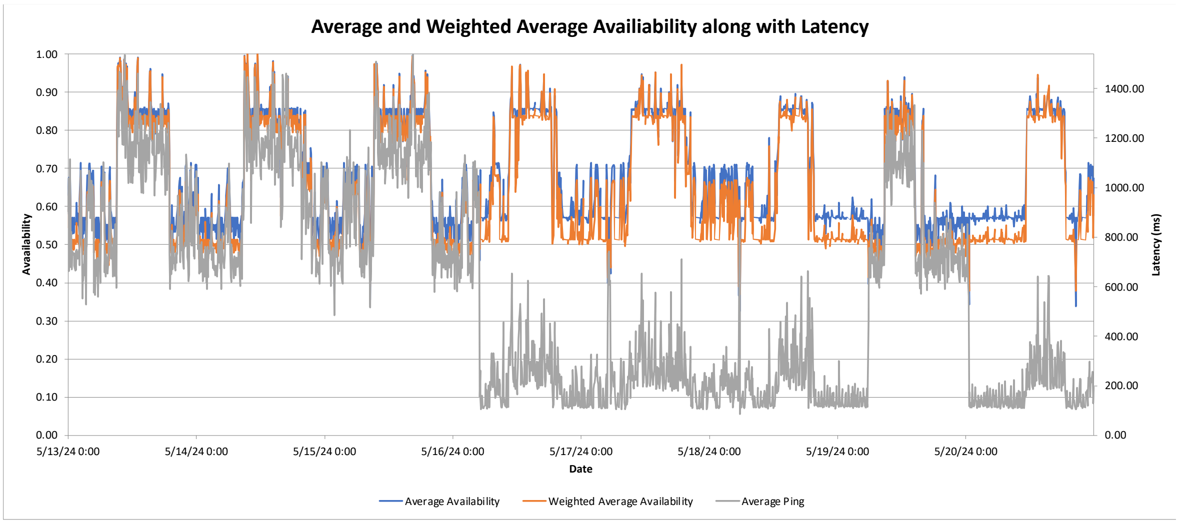


Figure 35. Average and Availability along with Latency SS52.

The average latency is high, with peaks exceeding 1,000 ms on several occasions. This suggests that the network in SS_{52} might be facing serious issues related to signal-to-noise ratio (SNR) 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. This drop in latency indicates a temporary improvement in network performance, possibly due to a reduction in noise levels or the resolution of a specific technical problem. However, this improvement is not long-lasting, as on May 19, latency abruptly increases again, reaching levels like those observed prior to May 16, only to return to 200 ms on the 20th. This behaviour could indicate the presence of an intermittent factor affecting network stability, such as fluctuating noise levels, recurring technical problems, or even external interference.

- Transmission Rates and Availability Graphs per repeater in SFB.

The graphs for each SFB provide a detailed view of the performance of the repeaters in terms of transmission rates and availability:

SFB_4 is located at 16 m from the SS and has 19 SM connected, as can be observed in the Table 11. Availability is extremely low and varies significantly, generally staying below 0.2

and peaking at 0.9 on occasion. Speeds indicate no data transmission or reception indicating that this SFB presents connectivity and stability problems, with very inconsistent data indicating significant infrastructure or signal quality problems.

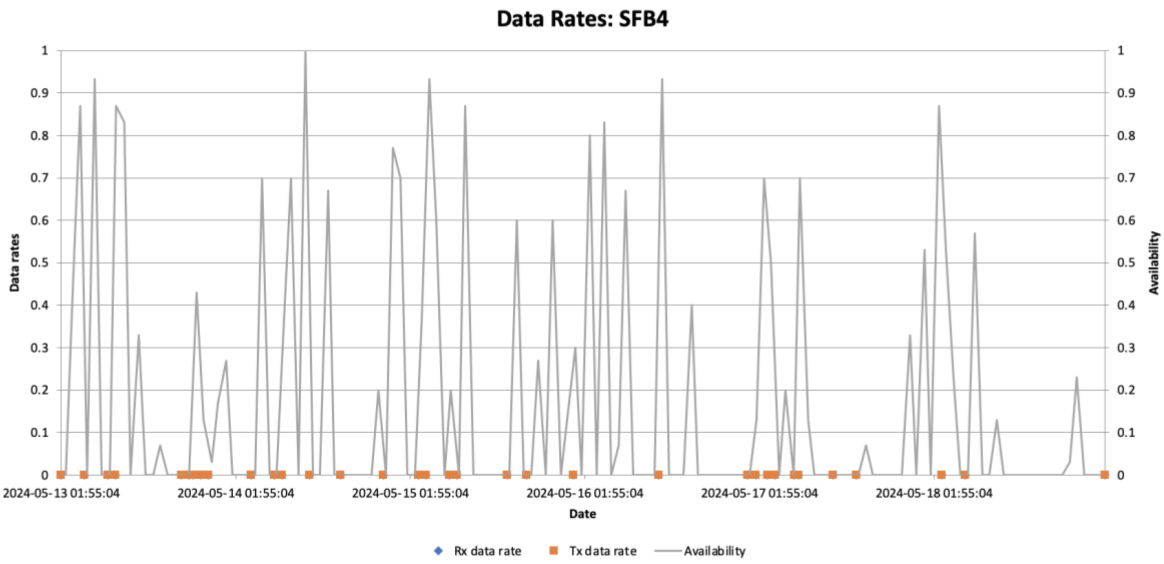


Figure 36. Data Rates SFB4 SS52.

SFB_8 is located at 18 m from the SS and has 20 SM connected, as can be observed in the Table 11. Availability is high and stable, around 0.95 - 1 throughout the period analysed, with only sporadic slight decreases. Transmission speeds are stable, remaining at 20 Mbps, however, reception speeds are low compared to those obtained in SS_{20}, around 5 Mbps. Although availability is high, the low receive speed could limit the overall system efficiency, indicating the need to investigate receiving performance issues.

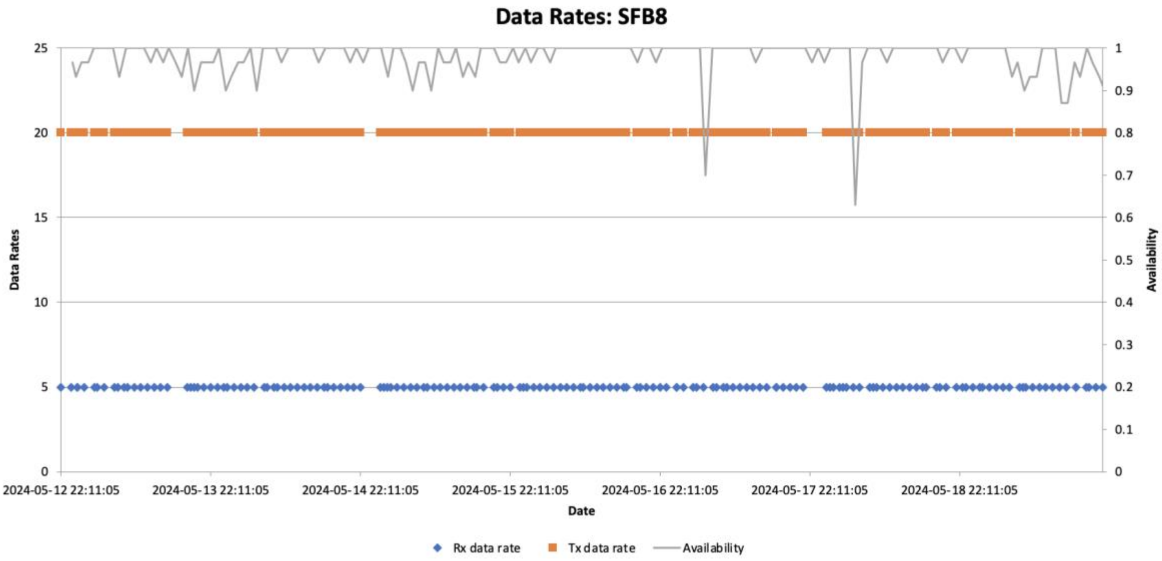


Figure 37. Data Rates SFB8 SS52.

SFB_{10} is located at 16 m from the SS and has 20 SM connected, as can be observed in the Table 11. Availability is high, fluctuating around 100%, with slight sporadic decreases. Like SFB_8, transmission speeds are stable and moderate (around 5 Mbps), but reception speeds are even lower (2 Mbps), which could indicate a problem similar to that observed in SFB_8. Despite reasonable availability, the low receiving speeds suggest performance issues that could affect the quality of service.

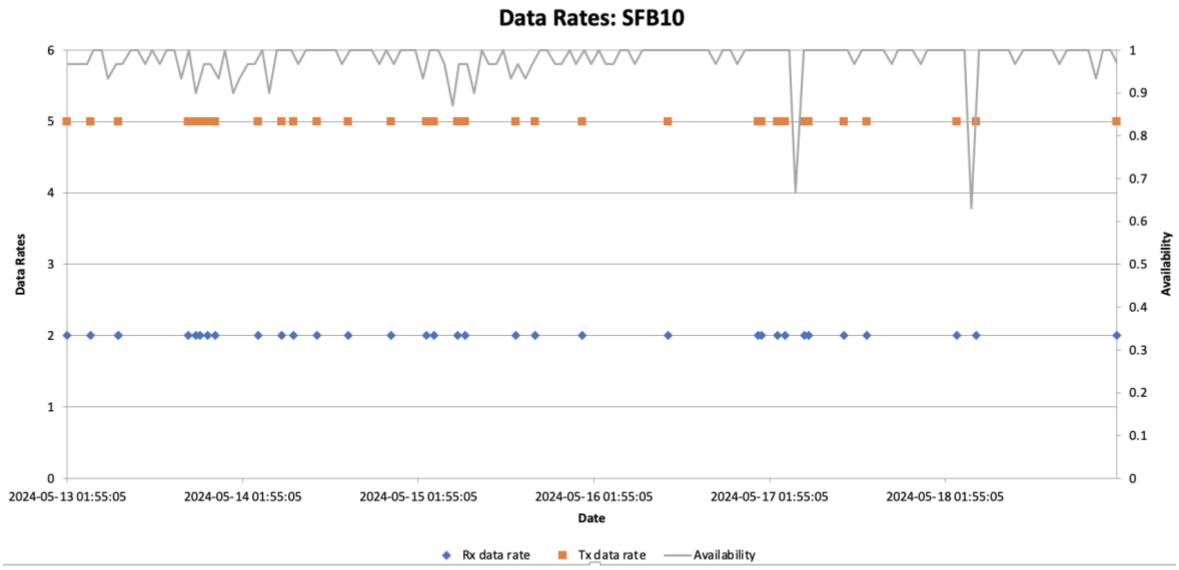


Figure 38. Data Rates SFB10 SS52.

SFB_{11} is located at 82 m from the SS and has 20 SM connected, as can be observed in the Table 11. The SFB11 exhibits very unstable behaviour in terms of availability over time. The availability fluctuates considerably, with several abrupt drops to 0, indicating that the repeater or the connection is completely interrupted during those periods.

Observing the graphs, it can be noted that when availability drops to 0, there is no transmit (Tx) or receive (Rx) rate data. This is consistent with the total loss of connectivity: when the repeater is not available, it cannot send or receive data, which is reflected in the absence of dots in the speed graphs. Since the speed data is obtained from GridValue, and the availability data from Grafana, it can be determined that there is consistency in this case, in the data collected by both software.

This fluctuation in availability could be indicative of various issues, such as intermittent interference or signal quality problems causing momentary disconnections, as well as the fact that SFB_{11} is a considerable distance from the SS, so there could be physical problems in the infrastructure due to distance, as well as faulty cables or loose connections, contributing to these drops. Since this SFB has 20 Smart Meters connected, it is possible that the load is too high for the equipment or there is a configuration issue causing instability.

External factors such as changes in environmental conditions or fluctuations in power supply could also be affecting availability.

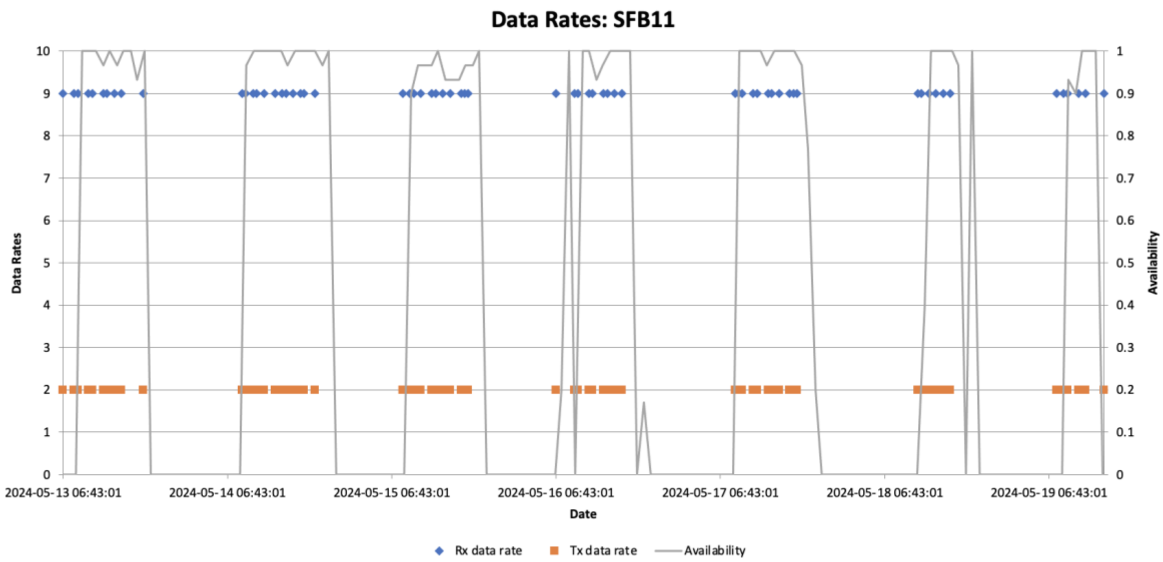


Figure 39. Data Rates SFB11 SS52.

SFB12 is located at 23 m from the SFB11 and has 19 SM connected, as can be observed in the Table 11. SFB12 shows similar behaviour to SFB11 in terms of availability fluctuations. Availability is generally high, but there are specific times when it drops, indicating intermittent interruptions in connectivity. During periods when availability is 0, the graph shows a complete absence of speed data. This implies that, as in SFB11, when the repeater is unavailable, it cannot handle data traffic.

When availability is high, transmit and receive speeds appear to be consistent and relatively stable, with Tx speeds around 70-90 Mbps and Rx around 80-100 Mbps. SFB12 is at 23 meters from SFB11, which is moderate, and has 19 Smart Meters connected. Despite this distance and moderate SM load, the drops in availability suggest that there could be issues related to signal-to-noise ratio (SNR) due to noise in the low voltage network, affecting connectivity. In addition, SFB12 connects to SFB11 according to the topology, so these availability issues may be directly related to those experienced by SFB11.

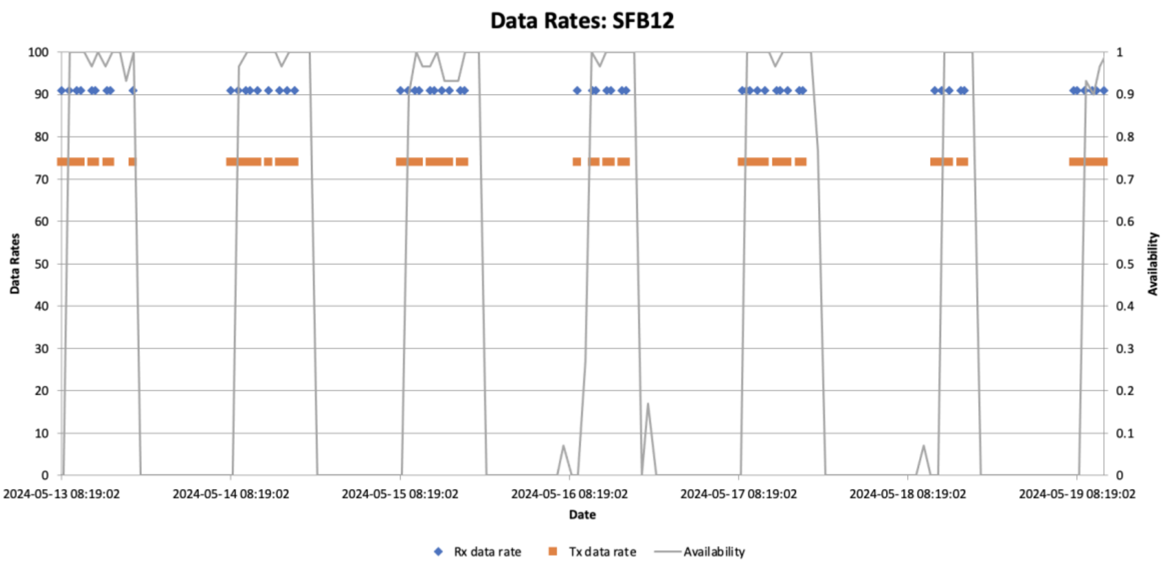


Figure 40. Data Rates SFB12 SS52.

SS_{52} shows moderate to low performance, with significant availability issues and high latency. SFB_{11} and SFB_{12} are particularly problematic, with fluctuations in availability directly affecting their ability to handle data traffic. These results suggest that factors, such as the distance between repeaters and the number of connected SMs, are negatively affecting network performance in this substation.

5.2.3 SS_{67} - LOW AVAILABILITY AND LOW LATENCY

Substation SS_{67} presents an interesting case for analysis due to its low availability, both in its simple and weighted average, despite having a relatively low latency. This analysis will focus on interpreting the graphs and tables provided to identify patterns, possible causes of problems and relationships between the different variables, as well as the variation observed in the graphs. Below is a summary table with the topology of this SS provided by MapInfo.

Line number	Previous SFB code	SFB code	Previous SFB distance	Number of SM
1	CT	SFB1	34	20
2	CT	SFB2	20	37
2	SFB2	SFB3	30	22
3	CT	SFB4	110	23
8	CT	SFB5	56	39
10	CT	SFB6	13	8
10	SFB6	SFB7	0	19
10	SFB7	SFB8	0	10
12	CT	SFB9	9	1

Table 12. Topological information for SS67.

a. Plot of Average and Weighted Average Availability along with Latency.

In the case of this substation, both the mean availability and the weighted mean availability remain at low levels throughout the period analysed. The notable difference between the two, with the weighted average being consistently lower, indicates that SFBs with more connected SMs are facing greater problems, which negatively affects the overall availability of the substation.

The graph in the Figure 41 shows that not only are the availability values low, but they also show some variability with occasional downward peaks, suggesting the presence of intermittent interruptions. These negative peaks could be associated with specific problems at specific times, perhaps related to overload or occasional interference.

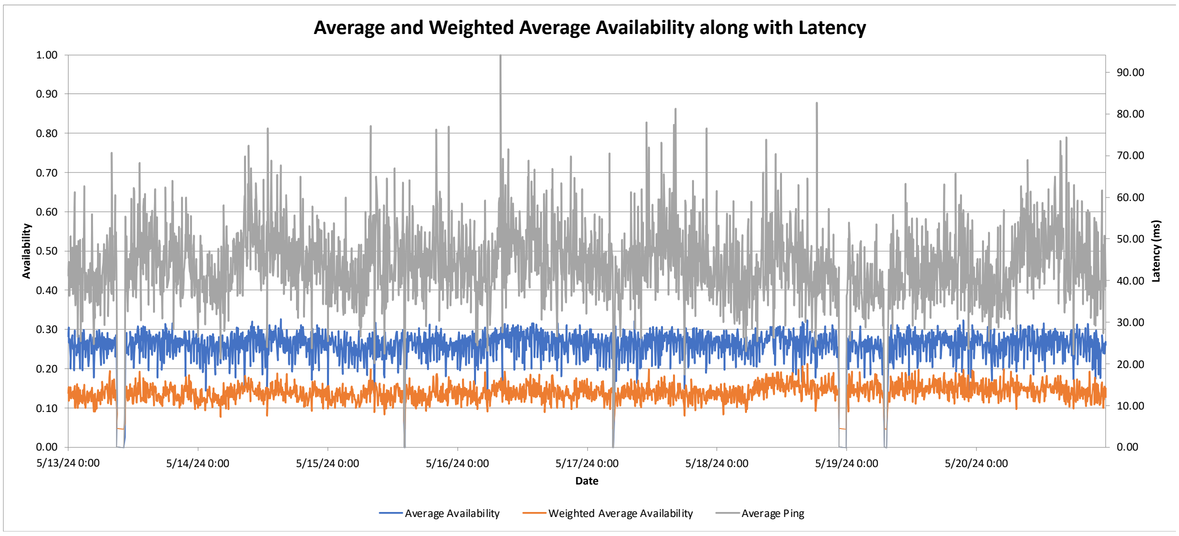


Figure 41. Average and Availability along with Latency SS67.

Average latency remains relatively low compared to other substations, with values ranging between 30 and 50 ms. However, significant latency peaks are observed at certain times, indicating variability in network performance. It is important to note that latency spikes do not always coincide with availability drops, suggesting that the causes of high latency may be independent of availability outages. These spikes may be due to temporary overloads or network infrastructure problems at specific times.

b. Transmission Rates and Availability Graphs per repeater in SFB.

The individual SFB plots provide a more detailed view of network performance at each of the repeaters, including variability in transmission rates and availability, some of these repeater's graphs are studied below:

SFB_1 is located at 34 m from the SS and has 20 SM connected, as can be observed in the Table 12. Transmit and receive rates are stable but low compared to the ones in SS_{20}, indicating that although the repeater is operating, it is operating at suboptimal performance. Availability, however, shows various peaks and a low value next to 0, which could be related to problems in the repeater infrastructure or interference at specific times.

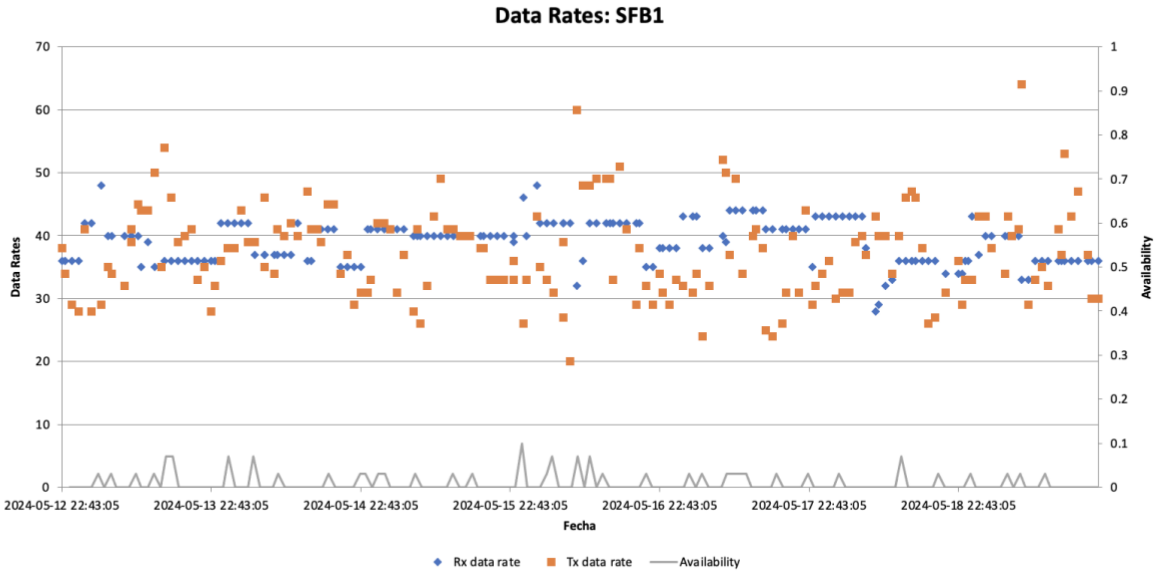


Figure 42. Data Rates SFB1 SS67.

SFB_4 is located at 110 m from the SS and has 23 SM connected, as can be observed in the Table 12. With the longer distance to the SS, SFB_4 shows stable data rate but low, compared to the ones in SS_{20}, and highly variable, and low availability, with significant drop peaks. The distance could be contributing to signal degradation and high variability in availability, which requires attention to improve stability.

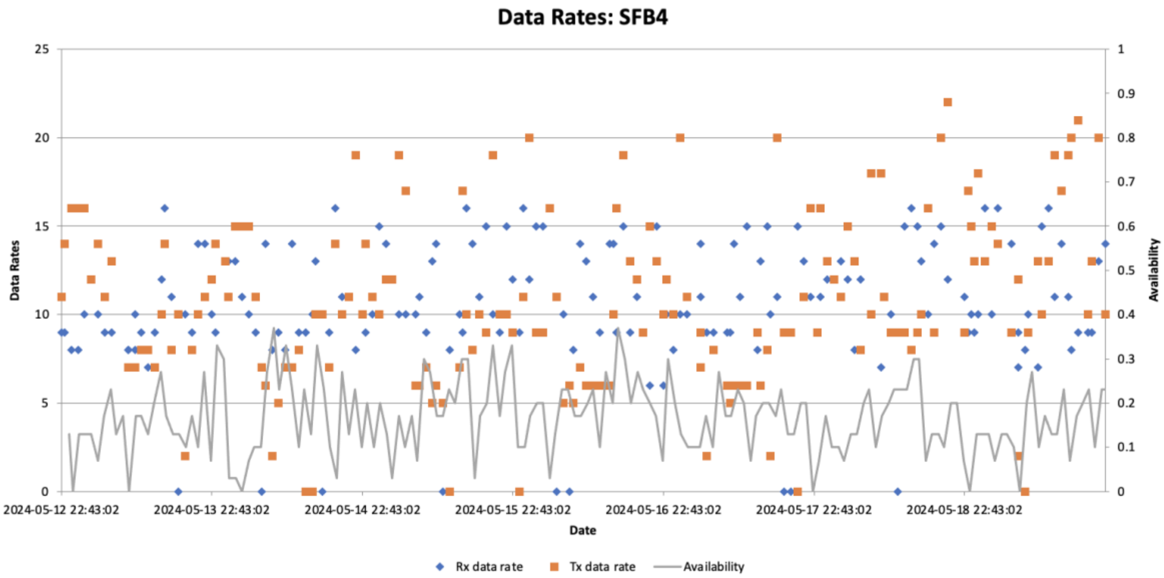


Figure 43. Data Rates SFB4 SS67.

SFB_6 is located at 13 m from the SS and has 8 SM connected, as can be observed in the Table 12. Despite its proximity to the SS, SFB_6 shows remarkable variability in availability, and low values, suggesting that additional factors, such as equipment problems or local interference, are impacting its performance.

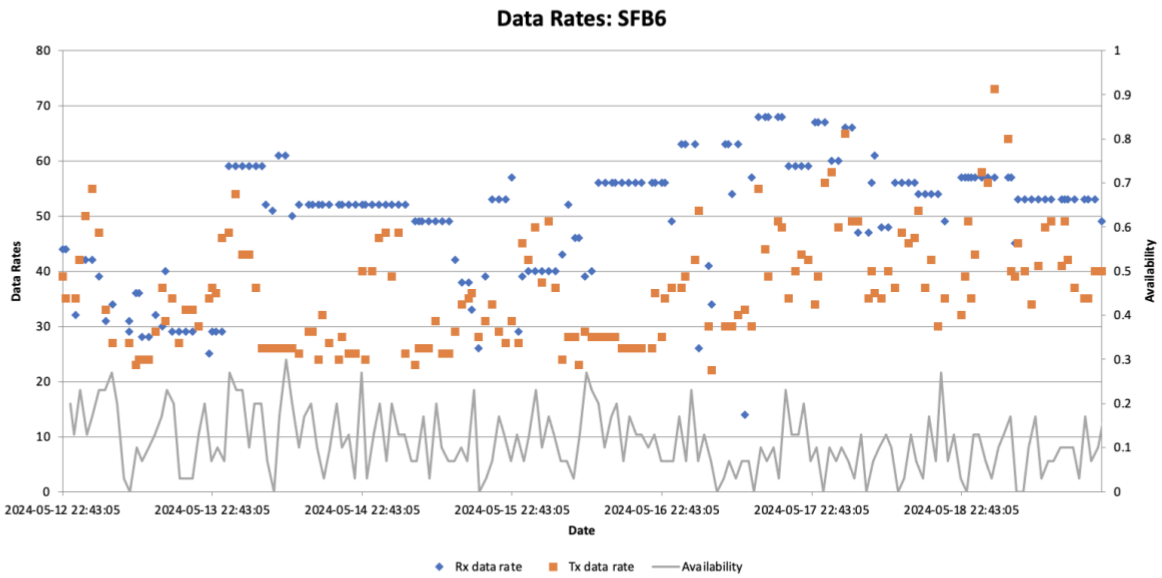


Figure 44. Data Rates SFB6 SS67.

Based on *Table 12* that complements the analysis of the plots, it can be observed that SFB_4, with the longest distance of 110 meters, shows low and highly variable availability, suggesting that distance significantly affects signal stability. This pattern is also observable in SFB_5, which although it has a shorter distance, its high SM load seems to contribute to the variability in availability. SFBs with more connected SMs, such as SFB_2 and SFB_5, tend to experience more variability in availability, which reinforces the hypothesis that higher workloads negatively affect network stability. To access the rest of the SS graphs, please see Annex II.

The SS_{67} substation faces significant challenges, especially in terms of availability, with high variability observed in multiple SFBs. The relationship between distance, SM load and network stability appears to play a key role in performance variability. Although latency is generally low, suggesting fast response times when the network is operational, frequent outages and variability in transmission rate and availability indicate that infrastructure or management improvements are needed to achieve more stable and consistent performance.

5.3 AVAILABILITY COMPARISON BETWEEN GRAFANA AND GRIDVALUE

In this section, a comparison between the availability metrics obtained from two different tools, Grafana and GridValue, across 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 to identify any discrepancies that may raise questions regarding the robustness of the measurements.

When comparing the availabilities reported for SS_8, SS_{10} and SS_{48}, it is necessary to consider that Grafana and GridValue use different methodologies to collect these metrics, which may explain the variations observed in the results.

The availability data collected by Grafana is based on ICMP (Internet Control Message Protocol). This method uses the percentage of lost packets, as previously discussed in earlier sections. In this project, the data has been configured to be collected every 5 minutes during the week of May 13-20, 2024. This frequent sampling makes Grafana particularly sensitive to short-term network interruptions, capturing granular variations in network stability that might otherwise go unnoticed.

Alternatively, GridValue provides two different types of availability data. The first, shown in the third column of the table, is a cumulative average of availability across all BPL relays in the network. This cumulative average is obtained by aggregating the availability metrics for each BPL relay over the same period, resulting in a smoother, long-term view of network availability. The second type of data, presented in the fourth column, is based on measurements taken every hour during the same week. These values are averaged over time to provide a different approximation of substation availability. Although this approach captures variations in availability, it is less granular than the Grafana data, so fluctuations in availability are seen with less accuracy and detail than with Grafana, but in more detail than with cumulative availability.

Secondary Substation	Availability Average (Grafana)	Availability Cumulative (GridValue)	Availability Average (GridValue)
SS8	84%	95.42%	94.28%
SS10	99%	99.60%	99.20%
SS48	85%	86.63%	89.22%

Table 13. Comparison between Grafana and GridValue for 3 SS.

When comparing Grafana and GridValue data for substations SS_8, SS_{10} and SS_{48}, some differences are observed. In the case of SS_8, Grafana reports an availability of 84%, while GridValue's cumulative average is 95.42%, and its more granular average is 94.28%. The significant difference between Grafana's data and GridValue's cumulative average suggests that Grafana may have detected multiple short outages that were not substantial enough to significantly affect GridValue's cumulative average. The latter tends to be more optimistic in its assessment of availability due to its lower granularity, since it takes a value every hour, which could give the impression of stability during this period. However, the closer alignment between Grafana and the more granular GridValue average indicates that, when similar temporal resolutions are considered, the results are more comparable, although still not identical.

In the case of SS_{10}, the differences between the two tools are minimal. Grafana reports 99% availability, GridValue's cumulative average is 99.60%, and its more granular average is 99.20%. This close alignment suggests a high degree of consistency between the two datasets, indicating that the grid in SS_{10} remained stable throughout the measurement period, with little or no short-term disruption. The small variations observed here could simply reflect the different methodologies, rather than any significant network problems.

In the case of SS_{48}, Grafana reports an availability of 85%, while GridValue shows a cumulative average of 86.63% and a more granular average of 89.22%. Although the discrepancy between Grafana and GridValue's cumulative average is not as pronounced as in SS_8, it still indicates that Grafana may be capturing minor outages that are smoothed out in GridValue's cumulative calculation. The slightly larger discrepancy between Grafana and the more granular GridValue average suggests that, even with more frequent sampling, differences still exist.

The differences between the availability measurements obtained from Grafana and GridValue can be attributed to several factors. Temporal sensitivity is one of them; Grafana's sampling at 5-minute intervals is likely to capture short-term disruptions or fluctuations in the network that may not have a lasting impact on overall performance. In contrast, GridValue's cumulative approach smooths out these momentary problems, reflecting a more averaged, long-term view. The more frequent measurements in GridValue's second dataset bring its results closer to Grafana's, but still show differences, potentially due to the inherent nature of each tool's data processing and capture.

The granularity of data collection in GridValue, which captures measurements every 5 seconds, allows for a very detailed analysis of short-term stability, identifying even the briefest transient problems. In comparison, Grafana, which takes data every 5 minutes, offers a less granular view but is still effective in identifying trends and more frequently occurring problems. However, this difference in sampling frequency means that GridValue can highlight more ephemeral network issues that might not be captured by Grafana. On the other hand, Grafana can provide a sufficiently detailed view without reaching the ultra-granularity of GridValue, which can be beneficial in terms of data processing and analysis over longer periods.

In addition, discrepancies may also arise due to factors not directly related to network performance, such as equipment failures, connectivity issues or metering errors. For example, if a device does not report data at certain intervals or experiences intermittent connectivity problems, this leads to lower availability figures.

Overall, the comparison of Grafana and GridValue availability metrics underscores the importance of understanding the context and methodology behind data collection when assessing grid performance. Grafana provides a detailed, short-term view that identifies transient issues, while GridValue provides a more cumulative, longer-term perspective on grid performance, albeit with less granularity due to the hourly frequency of its measurements. Both tools are valuable, but their differences highlight the need for a holistic approach to network monitoring and analysis, especially in complex and dynamic environments such as those found in BPL networks. The observed discrepancies emphasize that neither tool alone provides a complete picture; rather, it may be necessary to combine methodologies to fully understand and address network performance challenges.

Chapter 6. CONCLUSIONS AND FUTURE WORK

The conclusions and future work chapter summarizes the key results obtained during the development of the project, evaluating the implementation and performance of hybrid BPL technology and PRIME v1.4 in low voltage networks. Through the analysis of data collected in 68 secondary substations and using tools such as Grafana and GridValue, several of the stated objectives have been achieved, although challenges and areas requiring attention in future research have also been identified. These conclusions highlight the relevance of BPL technology in power grid modernization in general and, specifically for low voltage smart grid, as well as the need to continue refining measurement methodologies and expanding the scope of studies to ensure the robustness and applicability of results in broader contexts. In addition, suggestions are outlined for future work that seeks to consolidate the progress achieved and explore new opportunities for improvement in the implementation and evaluation of BPL technologies in low voltage networks.

6.1 CONCLUSIONS

This project has evaluated the implementation and performance of Corinex BPL and PRIME v1.4 (NB-PLC) hybrid technology in low voltage networks, using tools such as Grafana and GridValue to monitor the behaviour of 68 secondary substations. Throughout the development, several key objectives have been achieved, although challenges and areas for improvement have also been identified that require 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.

6.2 SUGGESTIONS FOR FUTURE WORK

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

a. Expansion of the Sample and Validation of Results

It is important to conduct additional studies with a larger number of secondary substations located in different geographic regions. This extension will improve the representativeness of the results, allowing validation of the current findings and ensuring that the observed patterns are consistent across different operating environments. This approach will also contribute to a better understanding of how local conditions and network-specific characteristics can influence BPL performance.

Implementing a cross-analysis using other measurement tools, in addition to Grafana and GridValue, would be interesting to verify the consistency of the data used. This cross-validation will help to refine the methodologies used and to identify the most appropriate tool or combination of tools for the ongoing evaluation of the performance of the technology used.

b. Development of Evaluation Criteria

From the data collected, clear performance thresholds need to be developed and defined to more accurately assess the success of BPL implementations. This includes determining specific criteria for latency, availability and other key parameters. These thresholds will serve as a reference for future implementations, facilitating early identification of problems and optimization of the technology.

Refining and standardizing data collection and analysis methodologies will ensure that measurements are consistent and comparable in future projects. This is key to establishing a solid foundation on which informed decisions can be made regarding the implementation and expansion of BPL in low-voltage networks.

c. Research of Alternative Technologies

It is essential 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 should not be limited to hardware and software, but should also consider the monitoring, management and optimization capabilities offered by these alternatives. In addition, it is important to recognize that there are multiple BPL standards, such as IEEE 1901, G.hn, and others, which may offer different advantages depending on the specific characteristics of the low voltage network.

Although the technology tested in this project, based on G.hn and developed primarily for home network applications, has shown reasonable results in its implementation in LV networks, it is crucial to explore whether other technologies or standards more specific to LV access could offer superior performance. A comprehensive comparative study that includes both technological solutions and applicable standards will identify possible improvements and more suitable alternatives, according to the needs of the network.

d. Continuous Improvement

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.

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ANNEX I - COMBINED STUDY OF THE SS

Attached is the complete table with the results of average availability, weighted average availability, and average ping for the 68 SS with hybrid BPL and PRIME v1.4 technology deployed.

Secondary Substation2	Availability Average	Availability Weighted Average	Ping Average (ms)
SS1	100%	100%	1331.12
SS2	0%	0%	0
SS3	99%	99%	2079.98
SS4	75%	76%	631.46
SS5	23%	43%	76.4
SS6	91%	89%	211.08
SS7	53%	45%	304.29
SS8	84%	84%	433.48
SS9	49%	27%	318.05
SS10	99%	99%	275.6
SS11	99%	99%	1184.09
SS12	97%	98%	432.39
SS13	94%	94%	658.42
SS14	97%	97%	490.66
SS15	39%	40%	78.11
SS16	100%	100%	287.8
SS17	38%	26%	210.44
SS18	81%	88%	214.5
SS19	77%	86%	406.3
SS20	100%	100%	64.39
SS21	89%	91%	1355.75
SS22	83%	88%	1045.61
SS23	97%	98%	1141.68
SS24	35%	28%	123.29
SS25	55%	33%	247.17
SS26	77%	79%	81.64
SS27	87%	87%	182.1
SS28	86%	84%	917.94
SS29	76%	75%	324.1
SS30	99%	100%	203.53
SS31	85%	85%	401.12
SS32	72%	89%	967.22
SS33	98%	99%	118.77
SS34	99%	98%	268.3
SS35	58%	50%	367.37
SS36	63%	57%	384.88
SS37	84%	87%	483.95
SS38	66%	66%	98.44
SS39	100%	100%	212.03
SS40	82%	83%	130.76
SS41	99%	99%	740.76
SS42	97%	97%	459.29
SS43	99%	99%	152.98
SS44	100%	100%	217.94
SS45	97%	99%	636.4
SS46	94%	96%	577.86
SS47	93%	94%	234.99
SS48	85%	76%	144.24
SS49	99%	99%	1074.06
SS50	0%	0%	0
SS51	97%	97%	233.23
SS52	69%	65%	570.41
SS53	99%	99%	1190.23
SS54	26%	30%	47.21
SS55	90%	89%	1903.88
SS56	61%	70%	241.17
SS57	0%	0%	0
SS58	81%	84%	527.05
SS59	96%	95%	594.14
SS60	79%	81%	152.42
SS61	99%	99%	676.27
SS62	72%	54%	379.98
SS63	94%	94%	277.01
SS64	77%	87%	140.76
SS65	78%	82%	444.08
SS66	97%	98%	745.5
SS67	26%	14%	43.38
SS68	100%	100%	104.46

Table 14. Summary of SS results..

It has been decided to show the above table in two new formats, the first, displayed in Table 15, represents the average availability ordered from highest to lowest.

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 15. Summary of SS results ordered by average availability.

The second display of Table 14 shows the SS sorted according to their weighted average availability in descending order.

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

Table 16. Summary of SS results ordered by weighted average availability.

Relating the patterns observed in the table sorted by average availability (Table 15) to the table sorted by weighted average availability (Table 16) provides a more comprehensive view and understanding of how the load distribution of the Smart Meters affects the overall performance of the substations. When analysing the two tables, several patterns and correlations can be observed that are more evident due to the organisation of the data.

In general, it is observed that in substations with high average availability, the weighted average is also usually high, and vice versa, regardless of the number of connected smart meters. However, in some cases, there are significant differences between both metrics, which in the case of showing a lower weighted average, indicates connectivity problems in repeaters with higher load.

Substations with high average and weighted average availability are not necessarily found to exhibit lower latencies. This indicates that latency is not always directly proportional to availability, suggesting that latency is influenced by additional factors, such as network noise or WAN infrastructure problems. Substations that fall in the ranking when weighted by the number of smart meters indicate that some repeaters with higher workloads are negatively affecting the overall performance. This suggests that, in cases where there is a drop in weighted availability, a more detailed assessment may be needed to identify and mitigate these bottlenecks.

When analysing the substations with high latencies, such as SS55, SS3, SS1, SS49, SS53 and SS22, and their location in the average and weighted availability tables, it can be noted that these substations are quite diversely distributed. This suggests that there is no clear and direct correlation between high latency and availability, either average or weighted. This pattern, or rather, the lack of a clear pattern, indicates that high latency may not be directly related to network availability in these substations. This reinforces the idea that latency is influenced by other factors that are not necessarily reflected in availability metrics. For example, WAN connectivity issues, line noise, or even congestion at other levels of the network could be affecting latency without significantly impacting availability.

Overall, while there are observable patterns between the availability average and the weighted average, the relationship with latency is not as evident, underlining the complexity of the network and the need for more detailed analysis to fully understand the behaviour of each substation.

ANNEX II - SFBS REPEATERS IN SS67

This annex shows the graphs that were not displayed in section 5.3.3 corresponding to the performance of the repeaters of substation 67.

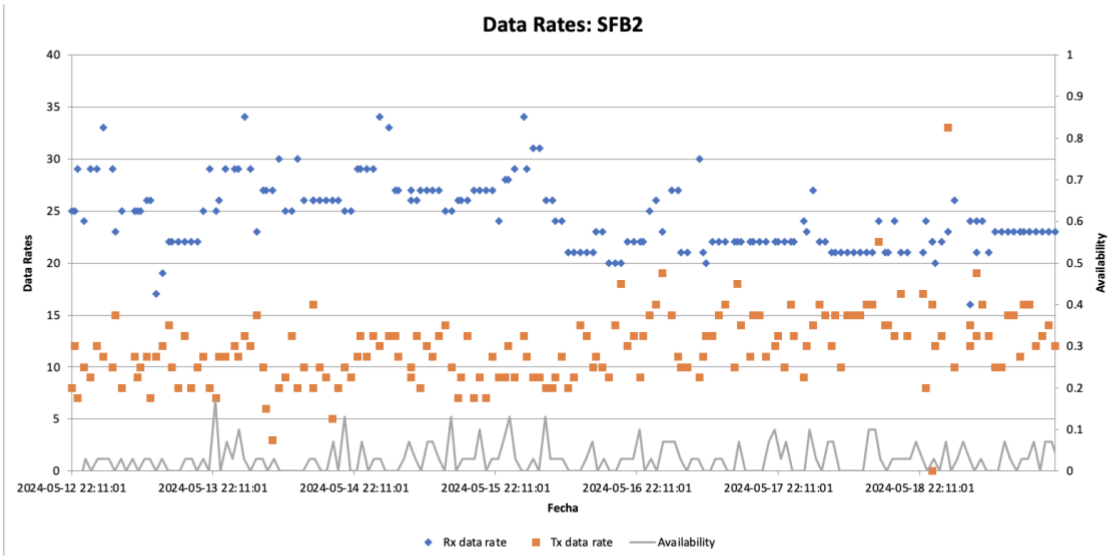

Figure 45. Data Rates SFB2 SS67.

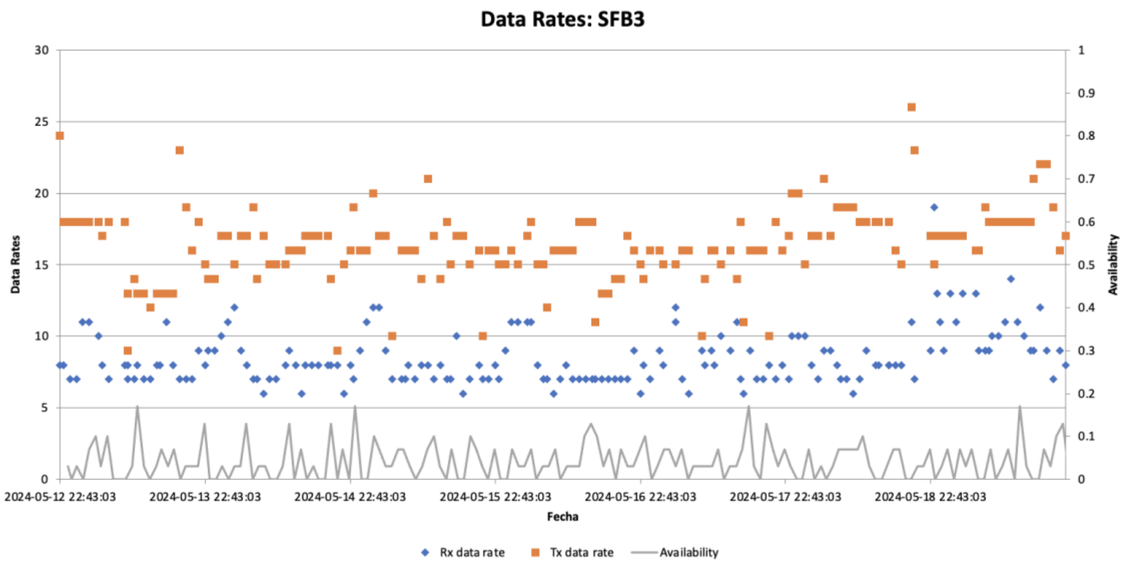

Figure 46. Data Rates SFB3 SS67.

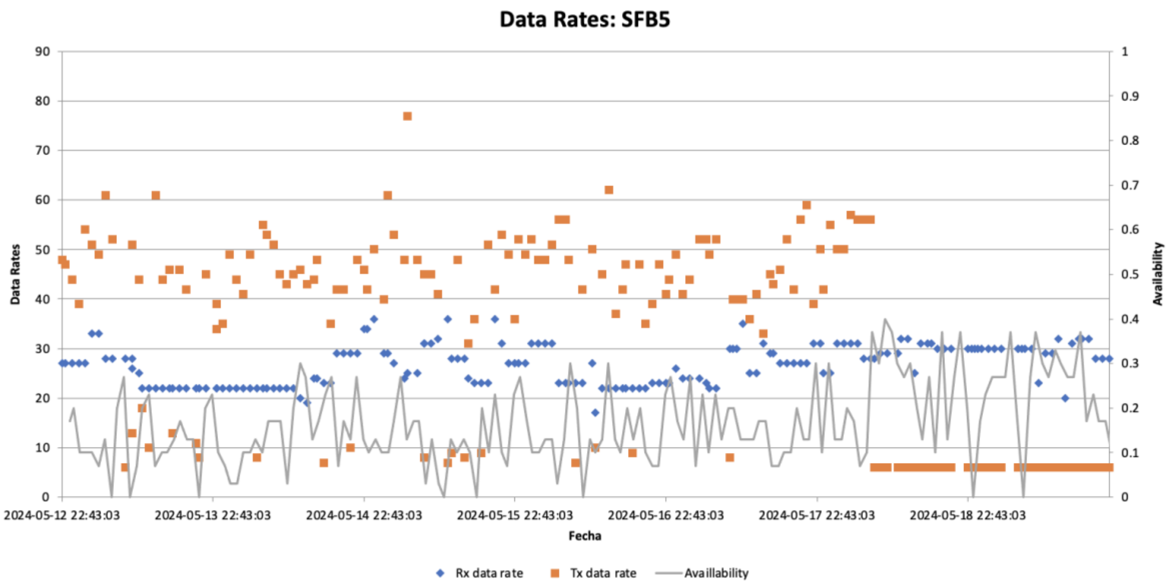

Figure 47. Data Rates SFB5 SS67.

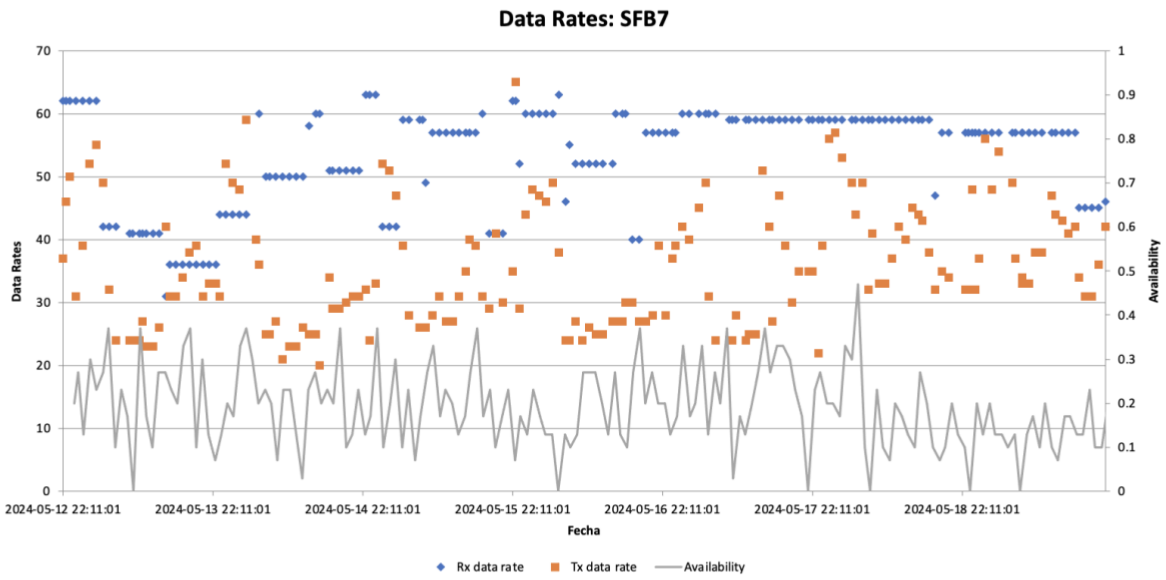

Figure 48. Data Rates SFB7 SS67.

ANNEX III - SUSTAINABLE DEVELOPMENT GOALS

This project not only aims to improve the efficiency and reliability of low-voltage grids, but also has a significant impact on several Sustainable Development Goals (SDGs) set by the United Nations. The SDGs that directly relate to the project's objectives and activities, as well as how this project contributes to their achievement, are presented below.

a. SDG7: Affordable and Clean Energy [29]

SDG 7 seeks to ensure access to affordable, reliable, sustainable and modern energy for all [29]. This goal recognises that access to energy is crucial for economic development, improved quality of life and environmental sustainability. Affordable and clean energy is fundamental to meeting other SDGs, as it boosts industry, improves health and education, and reduces poverty and inequality. The goal includes promoting renewable energy, improving energy efficiency and expanding sustainable energy infrastructure.

Target 7.1 aims to ensure universal access to affordable, reliable and modern energy services [29]. The project contributes to SDG 7 by improving the efficiency and reliability of the low-voltage electricity grid through the implementation of hybrid BPL and PRIME v1.4 technology. This improvement enables better real-time energy monitoring and management, resulting in more efficient and reliable distribution of electricity to end-users. In addition, by optimising the existing infrastructure without the need for large investments in new installations, the affordability of energy services is maintained.

Target 7.2 proposes to substantially increase the share of renewable energy in the energy mix [29]. The deployment of technologies such as BPL facilitates the integration of renewable energy sources into the electricity grid by improving communication and control between secondary substations and distributed generators. This is crucial to manage the intermittency and variability associated with renewables, thus contributing to a higher share of renewables in the energy mix.

b. SDG 9: Industry, Innovation and Infrastructure [29]

SDG 9 aims to build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation [29]. This goal recognises that modern infrastructure is the foundation of the economy and the well-being of societies. It promotes investment in innovative technologies, research and development, and job creation in industrial sectors. It also underlines the importance of sustainability in the construction and modernisation of infrastructure, to ensure that it is resilient to future challenges, such as climate change.

Target 9.1 proposes to develop reliable, sustainable, resilient and quality infrastructure [29]. The modernisation of the low-voltage grid infrastructure through the implementation of advanced technologies such as BPL and PRIME v1.4 promotes the creation of a more reliable and resilient energy infrastructure. This project is a clear example of technological innovation in the energy industry, which not only improves operational efficiency but also increases the resilience of the infrastructure to failures and disturbances.

Target 9.4 seeks to modernise infrastructure and retrofit industries to make them sustainable [29]. The project aligns with Target 9.4 by promoting the modernisation of electricity infrastructure through the adoption of advanced communication technologies that optimise the use of energy resources. This contributes to reducing technical losses and improving the sustainability of the power system.

c. SDG 11: Sustainable Cities and Communities [29]

SDG 11 aims to make cities and human settlements inclusive, safe, resilient and sustainable [29]. With rapid urban growth, this goal highlights the need to plan and manage urban development in ways that minimise environmental impacts and improve the quality of life for all citizens. It promotes access to affordable housing, the development of sustainable public transport, pollution reduction and the efficient management of urban resources. It also includes resilience to natural disasters and the protection of cultural and natural heritage.

Target 11.6 calls for reducing the per capita negative environmental impact of cities [29]. By improving the efficiency of the electric grid and facilitating the integration of renewable energies, the project indirectly contributes to the reduction of the negative environmental impact associated with electricity supply in urban settings. Optimising electricity management and reducing losses also contributes to reducing greenhouse gas emissions associated with power generation.

d. *SDG 13: Climate Action [29]*

SDG 13 calls for urgent action to combat climate change and its impacts [29]. It recognises that climate change is one of the greatest challenges of our time and affects all countries around the world, with disproportionate impacts on the most vulnerable communities. This goal promotes the reduction of greenhouse gas emissions, the integration of climate change measures into national policies and strategies, and the enhancement of capacity for adaptation and resilience to the effects of climate change.

Target 13.1 proposes to strengthen resilience and adaptive capacity to climate-related risks [29]. The project improves the resilience of electricity infrastructure, which is critical to addressing the challenges associated with climate change. A more robust and efficient power grid is less vulnerable to extreme weather events and can better adapt to fluctuations in energy demand.

Target 13.2 aims to incorporate climate change measures into national policies, strategies and plans [29]. The implementation of advanced grid technologies, such as those developed in this project, can serve as a model for future policies and strategies to mitigate the effects of climate change. The ability to efficiently monitor and manage energy consumption is key to implementing more sustainable energy policies.