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Power line Communication: Revolutionizing data transfer over electrical distribution networks

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ABSTRACT

Power Line Communication (PLC) is an emerging technology that utilizes existing electrical power infrastructure for data transmission. It enables communication over power lines, allowing devices to exchange information and access the internet through the power grid. This method offers numerous advantages, including widespread availability, cost-effectiveness, and easy deployment without the need for additional cabling. PLC has found applications in various domains, including smart grid management, home automation, industrial control systems, and Internet of Things (IoT) connectivity. This abstract provides an overview of PLC, highlighting its benefits, challenges, and key technologies. It also discusses the potential of PLC in transforming power distribution networks into intelligent and interconnected systems. Additionally, emerging trends and future directions for PLC research and development are explored, emphasizing the potential for enhanced reliability, speed, and efficiency in data transmission over power lines. This paper proposed a two way communication from source to load sides using BPSK and QPSK modulation techniques. Monte Carlo simulation is used to predict the transformer theoretical channel (AWGN) and compare the efficiency of the proposed methods. Randomly selected data from 10 k to 50 k size are used to compare the performance curve. Moreover, a test sound data is sent from the source side to the load side and it is observed that using the QPSK modulation technique has almost zero Bit Error Rate (BER).

1. Introduction

In today's hyper-connected world, where seamless communication and efficient data transfer have become a necessity, the quest for innovative technologies continues to push boundaries. Power Line Communication (PLC) emerges as a remarkable solution, leveraging existing electrical infrastructure to transmit data and signals over power lines. This transformative technology has gained significant attention due to its potential to revolutionize various industries, including smart grids, home automation, industrial automation, intelligent transportation systems, and beyond. With the ability to provide reliable and cost-effective communication, PLC holds tremendous promise for the future. The rapid growth of digitalization and the increasing demand for connectivity have propelled the need for efficient data transfer across vast networks. Traditional communication methods, such as wired connections or wireless technologies, have their limitations in terms of cost, coverage, and reliability. However, PLC presents an innovative approach by utilizing the extensive power grid infrastructure that already exists in most urban and rural areas [1].

Power lines, designed to deliver electrical power to homes, businesses, and industries, span across vast geographical regions, making them an ideal medium for data transmission. PLC taps into this infrastructure by superimposing data signals on the power lines, enabling simultaneous power distribution and data communication. This approach eliminates the need for laying additional communication cables or deploying new wireless infrastructure, resulting in significant cost savings and accelerated deployment of communication networks. The concept of using PLC is not entirely new. In fact, it dates back to the early 20th century when power lines were first utilized for low-speed telegraphy and signalling purposes. However, due to limited bandwidth and challenges in mitigating noise interference, early attempts at PLC were not as successful as envisioned. It was not until advancements in digital signal processing and modulation techniques that the true potential of PLC began to be realized [2].

Over the years, PLC has evolved significantly, transitioning from narrowband systems with limited data rates to broadband solutions capable of high-speed data transmission. The development of sophisticated modulation techniques, such as Orthogonal Frequency Division Multiplexing (OFDM), has played a crucial role in enabling higher data rates and improved signal quality over power lines. These advancements have paved the way for a wide range of applications and have opened up new possibilities for leveraging the power grid infrastructure beyond its original purpose [3].

One of the significant advantages of PLC is its ability to make

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efficient use of existing infrastructure. By utilizing power lines, which are already interconnected throughout cities, towns, and rural areas, PLC eliminates the need for costly and time-consuming infrastructure development. This advantage is particularly significant in areas where laying new communication cables or deploying wireless networks may not be feasible or economically viable. Cost-effectiveness is another key benefit of PLC. Organizations can leverage their existing power grid infrastructure, avoiding the expenses associated with deploying new communication cables or wireless equipment. This makes PLC an attractive option for applications such as smart grid systems, where extensive coverage is required to monitor and control energy distribution. Additionally, PLC can be integrated into home automation systems, allowing homeowners to control and monitor various aspects of their homes through power lines, reducing the need for separate communication infrastructure [4].

Reliability is a critical factor in any communication system, PLC offers inherent reliability advantages. Power lines are designed to handle high voltages and provide an uninterrupted power supply, making them robust and well-maintained. By leveraging the existing power grid infrastructure, PLC benefits from this reliability, offering a stable and secure communication channel. This is particularly valuable in critical applications such as smart metering, where accurate and consistent data collection is essential for effective energy management. Moreover, power lines cover vast areas, providing wide coverage for communication purposes. PLC signals can penetrate through walls and obstacles, making them suitable for applications such as home automation, where devices need to communicate across different rooms or floors. This wide coverage capability makes PLC a versatile solution for various industries and scenarios, from industrial automation in manufacturing plants to intelligent transportation systems on roads and highways [5].

To sum up, PLC represents a groundbreaking technology that leverages existing electrical infrastructure for efficient data transmission. By utilizing the power grid infrastructure, PLC offers cost-effective, reliable, and wide-ranging communication solutions for various industries and applications. As research and development efforts continue to advance this technology, we can anticipate a future where PLC plays a pivotal role in transforming how we communicate, connect, and interact with the world around us.

This paper tries to meet the frequency range of 2–150 kHz criteria. A novel PLC application is presented and validated by laboratory studies in this research. The proposed PLC methodology is based on Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) technologies across a live distribution transformer. The proposed PLC technique is intended to be a primary application when it comes to smart grid remote metering applications. Section 2 presents the understanding of PLC from historical background to evolutionary development. Section 3 will go through the standards that attempt to identify crucial variables for smart grid applications such as bandwidth modulation techniques, channel coding methods, operating frequency, and electromagnetic capacity restrictions

2. Understanding power line communication

The concept of using power lines for communication dates back to the early 20th century when it was primarily used for low-speed telegraphy and signaling purposes. However, the limited bandwidth and high noise interference posed significant challenges to effective data transmission. With advancements in digital signal processing and modulation techniques, the potential of PLC expanded, leading to significant research and development efforts in the late 20th century. PLC is a remarkable technology that utilizes existing electrical power distribution networks to transmit data and signals. Unlike traditional communication methods that rely on dedicated network cables or wireless connections, PLC taps into the infrastructure of power lines to enable data transfer through electrical wires [6].

The underlying principle of PLC lies in superimposing data signals onto the existing power lines. This is achieved by modulating the data signals at higher frequencies than the standard power frequency, allowing simultaneous power transmission and data communication. The power lines act as a medium for transmitting the data, carrying it to different locations through the extensive network of electrical infrastructure. To understand the technical aspects of PLC, it is essential to grasp the concept of frequency division multiplexing. Power lines are typically designed to carry electrical power at a specific frequency, such as 50 or 60 Hz, depending on the region. PLC takes advantage of the available frequency spectrum above the power frequency to transmit data signals. By dividing this frequency spectrum into multiple subcarriers, PLC enables the simultaneous transmission of multiple data signals, allowing for efficient and high-speed communication [7].

Orthogonal Frequency Division Multiplexing (OFDM) is a key modulation technique employed in PLC systems. OFDM divides the available frequency spectrum into numerous narrowband subcarriers, each of which can carry a portion of the data signal. These subcarriers are orthogonal to each other, meaning they do not interfere with one another, even when transmitted simultaneously. This characteristic of OFDM ensures robust and reliable data transmission over power lines, mitigating the impact of noise and signal attenuation [8].

PLC can be implemented using different modulation schemes, depending on the specific requirements of the application. One common modulation scheme is Amplitude Shift Keying (ASK), where the amplitude of the carrier wave is varied to represent digital data. Frequency Shift Keying (FSK) is another modulation scheme used in PLC, where the frequency of the carrier wave is changed to represent different data values. Phase Shift Keying (PSK) is yet another modulation technique, where the phase of the carrier wave is altered to encode data. The implementation of PLC involves several components and techniques to ensure efficient data transmission. One crucial aspect is the presence of PLC modems. These modems act as the interface between the electrical network and the data communication system, allowing the conversion of data signals into a format suitable for transmission over power lines [9].

PLC systems also incorporate sophisticated signal processing algorithms to enhance the quality and reliability of data transmission. Equalization techniques are used to compensate for signal distortion caused by the power line channel. Error correction mechanisms, such as Forward Error Correction (FEC), are employed to detect and correct data errors that may occur during transmission. Additionally, adaptive modulation techniques are implemented to optimize the data transmission based on the channel conditions, adjusting the modulation scheme and data rate dynamically.

The field of PLC continues to evolve, with ongoing research and development efforts aimed at addressing various challenges and expanding its capabilities. Signal attenuation and noise interference are among the primary obstacles faced by PLC systems. The quality of data transmission can be affected by factors such as power line impedance, noise from electrical appliances, and electromagnetic interference from other devices. To mitigate these challenges, researchers are exploring advanced signal processing techniques, sophisticated modulation schemes, and noise reduction algorithms [10].

Compatibility with existing power line infrastructure is another aspect that requires attention in PLC deployments. Different regions may have varying power line configurations, and ensuring interoperability across different network topologies is crucial. Standardization efforts play a significant role in establishing common protocols and specifications for PLC, allowing seamless integration and interoperability between different systems and devices. In recent years, PLC has witnessed significant advancements and found applications in various industries. The deployment of smart grid systems, where PLC enables bidirectional data exchange between utility companies and consumers, has gained considerable traction. Home automation systems, industrial automation, and intelligent transportation systems are other areas where PLC offers tremendous potential [11].

Finally, PLC physical layers were examined. In this study, PLC-based DCSK modulation was proposed [12]. By examining the effects of several factors, including the spreading factor, transmitted power, dependency parameter, impulsive noise index, and impulsive noise occurrence probability, valuable insights into the PLC system under consideration were determined in this study. [13] examines the secrecy performance of low-frequency PLC systems using a DCSK modulation technique in the face of several passive eavesdroppers. In order to achieve this, two distinct channel conditions are made, and an algorithm is also suggested to optimize secrecy while adhering to security and reliability restrictions. Another study \cite{home} has produced thorough knowledge regarding physical layer security concerns and raised awareness of the significance of PLC device design for bettering data communication security in home PLC systems where the eavesdropper is a PLC device. In the [14] the results that have been reviewed highlight how crucial it is to include innovations into PLC device designs or to reconsider the usage of unshielded power lines in electrical power grids when security concerns are raised in relation to the physical layer of PLC systems.

In conclusion, PLC is a groundbreaking technology that utilizes existing electrical infrastructure for efficient data transmission. By tapping into the power grid infrastructure, PLC eliminates the need for additional communication cables or wireless equipment, offering a cost-effective communication solution. With ongoing advancements and research efforts, PLC is poised to play a crucial role in shaping the future of communication systems in various sectors, enabling smarter and more connected environments [15].

3. Evolution of power line communication

The initial applications of PLC were primarily focused on narrowband systems, which offered limited data rates and were susceptible to noise and signal attenuation issues. However, advancements in technology and the introduction of broadband PLC marked a turning point in the evolution of this field. The development of OFDM and other modulation techniques enabled higher data rates and improved signal quality over power lines. PLC has been marked by significant advancements in technology and a growing understanding of the potential applications and benefits of using power lines for data transmission. From its early roots in basic telegraphy to the sophisticated broadband systems of today, PLC has undergone a remarkable journey of innovation and development [16].

In its nascent stages, PLC was primarily focused on narrowband systems, where low-speed telegraphy and signaling were the primary applications. These early systems faced numerous challenges, including limited bandwidth, high levels of noise interference, and signal attenuation over long distances. As a result, the scope of PLC was limited, and its potential for data transfer was yet to be fully realized. However, advancements in digital signal processing and modulation techniques played a pivotal role in expanding the capabilities of PLC. One of the key milestones in the evolution of PLC was the introduction of FDM, which allowed multiple signals to be transmitted simultaneously over different frequency bands. This breakthrough opened up new possibilities for data transfer and paved the way for future advancements in the field [17].

As the field continued to evolve, researchers and engineers focused on addressing the specific challenges associated with PLC. Efforts were made to develop advanced error correction techniques, noise cancellation algorithms, and adaptive modulation schemes to further enhance the performance of PLC systems. These advancements significantly improved the reliability and efficiency of data transmission over power lines. Furthermore, the evolution of PLC was not solely limited to technological improvements. Standardization bodies and organizations played a crucial role in establishing industry-wide guidelines and protocols to ensure interoperability and compatibility between different PLC systems. This standardization effort further accelerated the adoption and deployment of PLC solutions in various industries and sectors. With the ongoing advancements in PLC technology, researchers and engineers are continuously exploring new frontiers and pushing the boundaries of what can be achieved with PLC. Recent developments have focused on leveraging advanced signal processing techniques, such as advanced modulation schemes, channel estimation algorithms, and adaptive equalization, to further enhance the performance of PLC systems [18].

Moreover, the integration of PLC with emerging technologies like the Internet of Things (IoT) and 5G networks has opened up new possibilities for interconnected and intelligent systems. The combination of PLC and IoT enables seamless communication between a wide range of devices, creating a network of smart and interconnected systems that can revolutionize industries such as home automation, smart cities, and industrial automation. Looking ahead, the future of PLC appears promising. Continued research and development efforts are expected to further enhance the data rates, signal quality, and system reliability of PLC. The integration of PLC with renewable energy systems, electric vehicle charging infrastructure, and other emerging technologies will undoubtedly shape the future landscape of energy management and communication [19].

In conclusion, the evolution of PLC from its early telegraphy roots to the broadband systems of today represents a remarkable journey of innovation and development. Advancements in digital signal processing, modulation techniques, and standardization efforts have paved the way for the widespread adoption and deployment of PLC solutions across various industries. As technology continues to evolve, we can anticipate further advancements and applications of PLC, transforming the way we transfer data and communicate over electrical networks.

4. Advantages of power line communication

PLC offers several advantages that make it an attractive solution for data transfer and communication. These advantages include:

4.1. Infrastructure utilization

One of the major advantages of PLC is its ability to leverage existing electrical infrastructure, thereby maximizing the utilization of resources and minimizing the need for additional infrastructure development. By tapping into the vast network of power lines that crisscross cities, towns, and rural areas, PLC offers a cost-effective and efficient solution for data transfer and communication. Traditional methods of communication, such as laying new cables or deploying wireless networks, often require significant investment in infrastructure development. This process can be time-consuming, disruptive, and costly. However, with PLC, the infrastructure is already in place, as power lines have been established to distribute electricity to homes, businesses, and industries. By utilizing this pre-existing infrastructure, PLC eliminates the need for extensive construction projects, saving both time and resources [20].

The utilization of existing infrastructure also provides an advantage in terms of coverage. Power lines typically cover a wide geographical area, reaching even remote and rural locations. This extensive coverage allows PLC to penetrate into areas that may be challenging to connect through other means. Whether it is a densely populated urban area or a sparsely populated rural region, PLC can provide reliable communication services without the need for significant infrastructure expansion. Another benefit of leveraging existing infrastructure is the scalability it offers. As the demand for data transfer and communication grows, PLC can easily accommodate increased capacity without the need for major infrastructure upgrades. By making use of the power grid infrastructure, organizations can seamlessly scale up their communication networks to meet the evolving needs of their applications, whether it is in the field of smart grids, industrial automation, or home automation [21].

Additionally, the utilization of power line infrastructure brings about significant cost savings. Building a dedicated communication network from scratch can be a costly endeavor, involving the purchase of land, installation of cables, and deployment of network equipment. PLC eliminates these costs by utilizing the existing power lines, thereby reducing capital expenditures and operational expenses associated with infrastructure development and maintenance. Moreover, PLC offers a more environmentally friendly solution compared to the construction of new communication infrastructure. By making use of the existing power grid infrastructure, PLC minimizes the environmental impact associated with land disturbance, resource consumption, and energy consumption. This aligns with the principles of sustainability and reduces the carbon footprint associated with communication network expansion.

In conclusion, the utilization of existing electrical infrastructure is a significant advantage of PLC. By leveraging the extensive network of power lines, PLC offers a cost-effective, scalable, and environmentally friendly solution for data transfer and communication. The utilization of power line infrastructure maximizes resource utilization, ensures wide coverage, and contributes to the overall efficiency and reliability of the communication system. With PLC, organizations can optimize their communication networks while minimizing the need for additional infrastructure development.

4.2. Cost-Effective solution

PLC stands out as a cost-effective solution for data transfer and communication, offering several advantages that make it a financially appealing option for organizations across various industries.

One of the primary cost benefits of PLC is the utilization of existing infrastructure. Traditional methods of establishing communication networks often involve significant investments in infrastructure development, including the installation of dedicated communication cables or the deployment of wireless infrastructure. These projects can be time-consuming, resource-intensive, and require substantial capital expenditure. However, PLC takes advantage of the extensive power grid infrastructure that is already in place for electricity distribution. By leveraging existing power lines, PLC eliminates the need for laying new communication cables, which can be a costly endeavor, especially in densely populated urban areas or geographically challenging terrains. The use of pre-existing infrastructure significantly reduces the expenses associated with land acquisition, trenching, cable installation, and related construction costs. Additionally, PLC avoids the need for expensive rights-of-way negotiations and permits that would be required for deploying new communication infrastructure [22].

Moreover, the cost-effectiveness of PLC extends to operational expenses. With PLC, there is no need for ongoing maintenance and upkeep of separate communication infrastructure. The power grid infrastructure is already maintained and monitored to ensure uninterrupted electricity supply, and PLC can piggyback on this existing infrastructure, sharing maintenance costs with the power distribution system. This shared maintenance approach reduces operational expenses, making PLC a more cost-efficient communication solution. Additionally, the cost savings associated with PLC are not limited to the initial deployment and operational expenses. PLC also offers advantages in terms of scalability and future expansion. As the demand for data transfer and communication increases, organizations can easily scale up their PLC systems by adding more devices or utilizing advanced modulation techniques. This scalability allows organizations to expand their communication networks without significant infrastructure upgrades or additional investment, resulting in long-term cost savings [23].

Furthermore, the cost-effectiveness of PLC can be particularly significant in scenarios that require extensive coverage. Deploying new communication infrastructure, such as fiber-optic cables or wireless towers, in large geographical areas can be prohibitively expensive. In contrast, PLC can provide coverage over vast regions using the existing power grid infrastructure, eliminating the need for costly infrastructure expansion. This advantage is particularly beneficial in rural areas or developing regions where cost considerations play a crucial role in the feasibility of communication projects. Additionally, PLC's cost-effectiveness is enhanced by the potential for multipurpose utilization of the power grid infrastructure. Since power lines serve dual purposes of electricity distribution and data transfer, organizations can leverage the same infrastructure for multiple applications. For example, in smart grid systems, where real-time data communication is essential for efficient energy management, PLC can utilize the existing power lines for both electricity distribution and data transmission, resulting in cost savings compared to deploying separate communication networks. Furthermore, the cost advantages of PLC are not limited to a specific industry or sector. PLC's versatility enables its application in various domains, including industrial automation, home automation, intelligent transportation systems, and more. This versatility allows organizations to benefit from the cost savings of PLC across multiple applications, avoiding the need to invest in separate communication infrastructure for each use case.

In conclusion, PLC offers a cost-effective solution for data transfer and communication. By leveraging existing power grid infrastructure, PLC eliminates the need for extensive infrastructure development, reduces capital expenditure, and lowers operational expenses. The scalability, coverage capabilities, and potential for multipurpose utilization further enhance the cost advantages of PLC. As organizations seek efficient and cost-efficient communication solutions, PLC emerges as an attractive option that balances functionality with financial feasibility.

4.3. Wide coverage and penetration

PLC offers significant advantages in terms of wide coverage and penetration, making it a highly attractive solution for communication and data transfer across various settings and environments. One of the key strengths of PLC is its ability to provide extensive coverage. Power lines form a vast network that spans cities, towns, and even remote rural areas. This infrastructure reaches areas that may be challenging to connect through other means, such as wireless networks or dedicated communication cables. The existing power grid infrastructure ensures that PLC can reach a wide range of locations without the need for extensive infrastructure expansion. The coverage provided by power lines is particularly advantageous in scenarios where communication needs to span large distances, such as in industrial settings or smart grid applications. PLC enables reliable communication and data transfer across long distances, ensuring that information can be efficiently transmitted between different points within a given network. This capability is valuable in industries such as utilities, where monitoring and control systems need to communicate across vast geographical areas [24].

Furthermore, PLC is known for its ability to penetrate obstacles and reach areas that may be shielded from wireless signals. Power lines, being physically connected throughout a building or structure, can transmit signals through walls, floors, and other solid structures. This feature is particularly advantageous in environments where wireless communication signals may struggle to penetrate, such as underground facilities, high-rise buildings, or locations with dense infrastructure. The penetration capabilities of PLC enable seamless communication between devices located in different rooms, floors, or sections of a building. This makes it suitable for applications such as home automation, where devices in various areas of a residence need to communicate with each other.

PLC allows for efficient data transmission without the need for additional wiring or dedicated communication channels, simplifying the setup and reducing installation costs. In addition to indoor penetration, PLC can also extend its coverage outdoors, reaching devices located in open spaces. This opens up opportunities for applications in areas such as intelligent transportation systems, where traffic management systems can utilize power lines to communicate with traffic lights, sensors, and other roadside devices. PLC's outdoor coverage capabilities enable the creation of interconnected and intelligent systems that can enhance efficiency, safety, and sustainability in various transportation settings.

In conclusion, PLC offers wide coverage and penetration capabilities, making it a highly attractive solution for communication and data transfer. The extensive coverage of power lines allows PLC to reach diverse locations, including urban areas, rural regions, and challenging environments. The penetration capabilities of power lines enable communication through obstacles and ensure seamless connectivity between devices in different locations. The wide coverage and penetration of PLC contribute to its versatility, reliability, and applicability in various industries and sectors.

4.4. Reliability and stability

PLC offers inherent reliability and stability, making it a robust communication solution for various applications. By leveraging the power grid infrastructure, PLC benefits from the reliable and stable nature of power lines, ensuring continuous and uninterrupted data transmission. One of the key factors contributing to the reliability of PLC is the design and construction of power lines themselves. Power lines are engineered to withstand various environmental conditions, such as extreme temperatures, weather fluctuations, and physical stresses. They are built with materials and configurations that provide resilience against external factors, ensuring their long-term stability and performance. As a result, the infrastructure that supports PLC is inherently reliable, providing a solid foundation for communication networks.

Furthermore, the use of power lines for data transmission allows PLC to benefit from the extensive infrastructure monitoring and maintenance practices that are already in place for the power grid. Power companies routinely monitor power lines for faults, perform maintenance activities, and quickly respond to any disruptions. This proactive approach to infrastructure management ensures that any issues affecting the power grid are promptly addressed, benefiting the stability and reliability of PLC systems running on the same infrastructure.

PLC systems also employ error correction techniques and robust modulation schemes to enhance the reliability of data transmission over power lines. These techniques help mitigate the effects of noise, signal attenuation, and interference that may occur during data transfer. By adapting to the changing conditions of the power line channel, PLC systems can maintain a reliable and stable communication link, ensuring the accurate and timely delivery of data. Additionally, the stability and reliability of PLC are particularly valuable in critical infrastructure applications, such as smart grids and industrial automation. In smart grids, PLC enables real-time monitoring and control of energy distribution, allowing utilities to respond swiftly to changes in demand or faults in the system. PLC's reliable and stable communication ensures the seamless exchange of information between different components of the smart grid, enabling efficient energy management and grid optimization [25].

In industrial automation, PLC plays a vital role in ensuring the reliable and continuous operation of interconnected systems. PLC allows for the real-time exchange of control signals, sensor data, and feedback loops between various devices and components on the factory floor. The stability and reliability of PLC communication are essential in maintaining the synchronization and coordination of industrial processes, minimizing downtime, and optimizing productivity [26].

In conclusion, PLC offers inherent reliability and stability due to the characteristics of the power grid infrastructure it utilizes. The design and construction of power lines, along with the existing maintenance practices, ensure a robust and stable communication channel for PLC. The stability of power lines, along with error correction techniques and modulation schemes, further enhance the reliability of data transmission over PLC systems. Whether in critical infrastructure applications or other industries, the reliability and stability of PLC make it a trusted communication solution for organizations seeking uninterrupted and dependable data transfer capabilities.

4.5. Scalability and flexibility

PLC offers significant advantages in terms of scalability and flexibility, allowing organizations to expand their communication networks and adapt to evolving requirements with ease. The inherent characteristics of PLC make it a versatile solution that can accommodate increasing data transfer capacity and support diverse applications. One of the key benefits of PLC is its scalability. As the demand for data transfer and communication grows, organizations can seamlessly scale up their PLC systems to meet evolving needs. Unlike traditional communication methods that may require extensive infrastructure upgrades or the deployment of new networks, PLC allows for the expansion of communication capabilities without significant modifications to the existing infrastructure. This scalability is possible due to the widespread deployment of power lines that form the backbone of the PLC system.

Furthermore, PLC systems can be integrated with existing communication networks, enabling seamless interoperability with other technologies and protocols. This integration allows organizations to leverage the benefits of PLC while maintaining compatibility with other systems, such as wireless networks or Ethernet-based networks. PLC can serve as a complementary communication solution, filling the gaps where other technologies may have limitations or coverage issues. The flexibility of PLC extends to its application across various industries and sectors.

PLC can be utilized in smart grids to enable bidirectional communication between utility providers and consumers, facilitating real-time energy management and demand-response systems. In home automation, PLC enables the transmission of control signals and data between different devices, such as smart appliances, thermostats, and lighting systems, offering a convenient and reliable solution for building automation. PLC is also well-suited for industrial automation, where it supports the exchange of data between sensors, actuators, and control systems. The flexibility of PLC allows for the integration of diverse industrial protocols, enabling seamless communication across different components of the automation system. This flexibility enables organizations to optimize their industrial processes, improve efficiency, and respond quickly to changing production demands [27].

Moreover, the flexibility of PLC makes it suitable for intelligent transportation systems. PLC can be utilized for traffic signal control, vehicle-to-infrastructure communication, and data exchange between traffic management centers. The scalability of PLC enables the expansion of communication capabilities as transportation networks grow and evolve.

In conclusion, PLC offers scalability and flexibility, allowing organizations to expand their communication networks and adapt to changing requirements. The scalability of PLC enables organizations to increase data transfer capacity without extensive infrastructure upgrades, while the flexibility allows for system configuration, integration with existing networks, and application across various industries. Whether it is in smart grids, home automation, industrial automation, or intelligent transportation systems, PLC's scalability and flexibility make it a versatile solution for organizations seeking adaptable and future-proof communication capabilities.

4.6. Easy deployment and integration

PLC offers the advantage of easy deployment and integration, making it a convenient choice for organizations seeking efficient and streamlined communication solutions. The inherent characteristics of PLC, coupled with the utilization of existing power grid infrastructure, simplify the deployment process and enable seamless integration with other systems. One of the primary benefits of PLC is the straightforward deployment process. Unlike other communication methods that may require extensive construction or installation, PLC can be implemented quickly and with minimal disruption. Since power lines are already in place for electricity distribution, organizations can leverage the existing infrastructure without the need for additional cabling or network setup.

The deployment process typically involves connecting PLC devices to power outlets or directly integrating them into electrical panels. PLC devices, such as modems or adapters, are designed to be easily installed by simply plugging them into power sockets. This plug-and-play functionality eliminates the need for complex installation procedures and reduces deployment time. Additionally, the deployment of PLC systems does not require specialized technical expertise. The simplicity of the installation process allows organizations to deploy PLC networks without extensive training or specialized knowledge. This ease of deployment makes PLC accessible to a wider range of users, including small businesses and residential applications. Moreover, PLC offers seamless integration capabilities with existing communication networks and protocols. Organizations can integrate PLC systems into their existing infrastructure, such as Ethernet networks, wireless networks, or Internet of Things (IoT) platforms. PLC can serve as a complementary communication solution, expanding the reach and coverage of the existing network [28].

The integration of PLC with other systems is facilitated by the availability of standardized protocols and interfaces. PLC devices typically support various communication protocols, such as TCP/IP, UDP, or Modbus, enabling interoperability with different devices and systems. This compatibility ensures that PLC can seamlessly exchange data with other networked devices and enables organizations to leverage the benefits of PLC without disrupting their existing communication infrastructure. Furthermore, the ease of deployment and integration of PLC systems allows for rapid deployment in various applications. For instance, in smart grid implementations, PLC can be quickly deployed across the electrical distribution network, enabling real-time communication between utility providers and end-users. This enables efficient energy management, demand-response systems, and integration of renewable energy sources into the grid.

In home automation, PLC offers a convenient solution for connecting and controlling smart devices within a household. The ease of deployment allows homeowners to quickly set up and expand their home automation systems, providing enhanced comfort, energy efficiency, and convenience [29].

In industrial automation, PLC can be seamlessly integrated with existing control systems, enabling real-time data exchange between sensors, actuators, and control devices. The straightforward deployment and integration of PLC facilitate the implementation of efficient and responsive automation processes, optimizing productivity and reducing downtime.

Additionally, the ease of deployment and integration of PLC makes it a suitable solution for intelligent transportation systems. PLC can be deployed in traffic management centers and seamlessly integrated with existing traffic control infrastructure. This integration enables efficient traffic signal control, vehicle detection, and communication between transportation management systems. The ease of deployment and integration of PLC systems also allows for scalability. As the need for communication expands, organizations can easily add more PLC devices or access points to the existing power grid infrastructure, extending the coverage and capacity of the communication network [26].

In conclusion, PLC offers the advantage of easy deployment and integration, simplifying the implementation process and enabling seamless integration with existing communication systems. The plug-and-play nature of PLC devices, coupled with the utilization of existing power grid infrastructure, facilitates quick and straightforward deployment. The compatibility with standardized protocols and the ability to integrate with different networks and devices further enhance the ease of integration. Whether in smart grids, home automation, industrial automation, or intelligent transportation systems, the easy deployment and integration of PLC make it a convenient and accessible communication solution for organizations seeking efficient and hassle-free implementation.

4.7. Security

PLC offers robust security measures, ensuring the confidentiality, integrity, and availability of data transmitted over power lines. The security features of PLC systems protect against unauthorized access, data breaches, and cyber threats, making it a secure communication solution for sensitive applications. One of the key security advantages of PLC is its inherent physical layer security. Unlike wireless communication methods, PLC operates through power lines, which act as a physical barrier against unauthorized access. The physical medium of power lines makes it more difficult for malicious actors to intercept or manipulate the transmitted data, as they would need physical access to the power lines or the premises where they are installed.

Additionally, the transmission of data over power lines is typically encrypted, providing an additional layer of security. Encryption techniques, such as Advanced Encryption Standard (AES) or Data Encryption Standard (DES), are commonly used to protect the confidentiality and privacy of data transmitted through PLC systems. Encryption ensures that even if unauthorized access occurs, the intercepted data remains unreadable and unusable to the attackers.

Furthermore, PLC systems often employ authentication and access control mechanisms to prevent unauthorized devices from accessing the network. Only authorized devices with proper credentials can establish a connection and participate in the communication. This authentication process safeguards against unauthorized devices attempting to gain access to the network and helps maintain the integrity of the communication system. To ensure the integrity and authenticity of data transmitted over power lines, PLC systems utilize digital signatures and cryptographic protocols. These mechanisms verify the origin and integrity of the transmitted data, preventing tampering or data manipulation during transmission. Digital signatures provide assurance that the data received is from a trusted source and has not been altered in transit. PLC systems also incorporate measures to protect against cyber threats and attacks. Intrusion detection and prevention systems are implemented to monitor the network for suspicious activities or potential security breaches. These systems can detect and block unauthorized access attempts, ensuring the network remains secure [30].

Moreover, PLC networks can be segmented and isolated to minimize the impact of a security breach. By dividing the network into separate segments or virtual private networks (VPNs), organizations can restrict access to sensitive data and limit the potential damage caused by a security incident. Segmentation helps contain the impact of a security breach and prevents unauthorized access to critical systems or information. Additionally, the security of PLC systems is further enhanced through regular security audits, vulnerability assessments, and updates. Organizations implementing PLC networks continuously monitor and evaluate the security of their systems, ensuring that any potential vulnerabilities are identified and addressed promptly. Regular software updates and patches are applied to mitigate newly discovered vulnerabilities and strengthen the security posture of the PLC network. Furthermore, the use of standardized security protocols and encryption algorithms in PLC systems ensures compatibility with existing security infrastructure and practices. Organizations can leverage their existing security measures, such as firewalls, intrusion detection systems, and Security Information and Event Management (SIEM) solutions, to enhance the security of their PLC networks. This integration with established security practices ensures a comprehensive and robust security framework [31].

4.8. Compatibility with multiple applications

PLC offers compatibility with multiple applications, making it a versatile communication solution that can cater to diverse industry needs. The flexibility and adaptability of PLC enable its integration into various domains, ranging from residential applications to industrial automation and smart grid systems. One of the key advantages of PLC is its ability to support different types of data transfer, including voice, video, and data signals. This compatibility allows PLC to cater to a wide range of applications and communication requirements. Whether it is transmitting high-quality audio and video streams in home entertainment systems or facilitating data transfer in industrial control systems, PLC provides a reliable and efficient communication medium.

In residential applications, PLC can be used for home automation, enabling the control and monitoring of various devices and systems within a household. With PLC, homeowners can easily integrate smart appliances, lighting systems, security cameras, and thermostats, creating a connected and intelligent living environment. The compatibility of PLC with different protocols and devices ensures seamless integration and interoperability within the home automation ecosystem. Furthermore, PLC can be employed in building management systems to monitor and control various building functions, including HVAC (heating, ventilation, and air conditioning) systems, lighting, access control, and energy management. The compatibility of PLC with different building automation protocols allows for efficient communication between devices and systems, enabling centralized control and optimization of building operations.

In the industrial sector, PLC finds extensive use in automation and control systems. PLC enables real-time communication between sensors, actuators, and control devices, allowing for precise and coordinated control of industrial processes. The compatibility of PLC with diverse industrial protocols, such as Modbus, Profibus, and DeviceNet, ensures seamless integration with existing automation systems, enabling efficient data exchange and synchronization.

Moreover, PLC can be integrated into intelligent transportation systems for traffic management and vehicle-to-infrastructure communication. PLC compatibility with different transportation protocols enables the transmission of traffic data, control signals, and real-time information between traffic management centers, traffic lights, and vehicles. This integration enhances the efficiency and safety of transportation networks. Additionally, PLC is extensively used in smart grid systems for energy management and communication between utility providers and consumers. PLC allows for bidirectional communication, enabling real-time data exchange, load monitoring, and demand-response systems. The compatibility of PLC with smart grid protocols, such as DNP3 (Distributed Network Protocol) and IEC 61850, ensures seamless integration with existing smart grid infrastructure [32].

5. Material and methods

In order to send data over distribution transformers, additional circuit devices both in the primary and secondary sides are required to maintain data reliability. This yields extra cost and security concerns should be maintained at the high voltage side. However, the suggested method for PLC does not need to have any additional device except to define maximum gain at a specific frequency [33–35].

5.1. Distribution transformer

In this work, a 400kVA, Dy11, 11/0.416 kV distribution transformer is measured as shown in Fig. 1 to provide example frequency characteristics. The distribution transformers are fed through power cables/lines which have specific high frequency characteristics.

It was observed that the bandwidth of the resonance band could be used as a communication channel for PLC and the proposed model is suitable even for sending large data. A method for observing variable time and current at specific time intervals has been introduced. It has been observed that low access impedances have arisen due to the reduction of the signal transmitted by the simulation results based on IEEE 1901.2 and the increase of the operating current by the PLC devices.

Fig. 1. Real time experiments in laboratory environment (400kVA, Dy11, 11/0.416 kV).

5.2. Line model

To achieve a realistic study 'line' model is also used in this study. The transmission line is modeled as a 2-port network and its related coefficients are calculated as below:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{1}$$

where A = D = -1.0144-j0.0209, B = Z = 3.12 + j4.455, C = 0.009. In Eq. (1). V_1 and V_2 are the sending and receiving voltages, I_1 and I_2 are the sending and receiving currents, and A, B, C, D are the line parameters. These parameters are obtained experimentally, i.e. no-load and short circuit tests of the line model and AC analysis results are given in Fig. 2 and it seems that around 1 kHz line has the highest resonance frequency. The overall experimental design is seen in Fig. 3 in the laboratory environment.

As it is seen the Fig. 4, input frequency of the source is changed from 50 Hz to 800 kHz and the high frequency response is obtained both using phase to phase connection of the secondary windings. Maximum gain is calculated as in Eq. (2).

$$Gain = V_s N_r \tag{2}$$

where N_r is the transformer turns ratio. From now on this response is called as communication channel of the transformer.

The transformer has a maximum gain of 70 at 410 kHz in Fig. 4. This channel will further be used for data and voice transmission for real time studies over transmission line and distribution transformer with a bandwidth of 100 kHz in Fig. 5.

5.3. Laboratory experiments

Two modulation techniques are used and compared to their efficiency for testing PLC performance over distribution transformer, i.e. BPSK and QPSK. Fig. 6 and Fig. 7 show the application of BPSK and QPSK techniques with the use of a distribution transformer, respectively.

Monte Carlo simulation technique is used to simulate the AWGN channel and compared to BPSK and QPSK channels. A randomly selected from 10 k to 50 k data is sent through from primary to secondary as shown in Fig. 8 and Fig. 9.

From Fig. 10, QPSK modulation yields an almost lower bit error rate compared to BPSK modulation. Fig. 11 shows the performance of the test sound wave (thermo.wav, "In this house, we obey the laws of thermodynamics!") which starts from low frequency to high frequency. QPSK modulation technique presented almost zero BER over transferred from

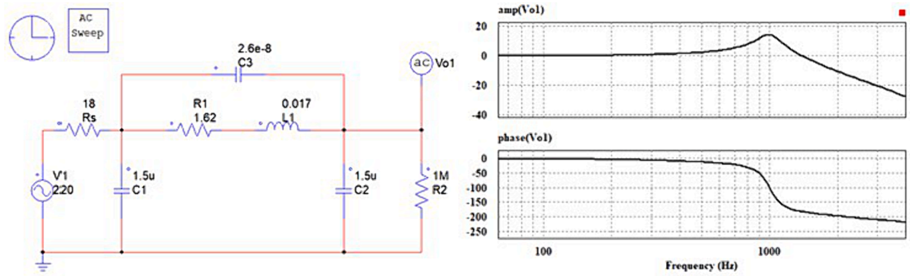

Fig. 2. No-load and short circuit tests of the line model and AC analysis results.

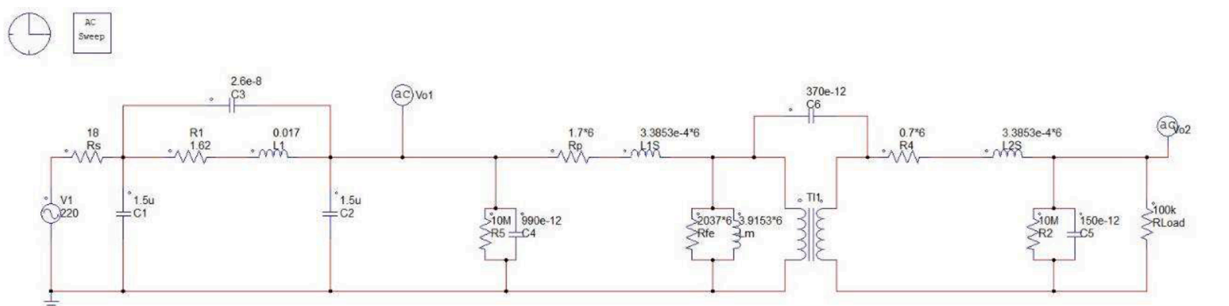

Fig. 3. Experimental circuit using both transmission line and a distribution transformer in the laboratory environment.

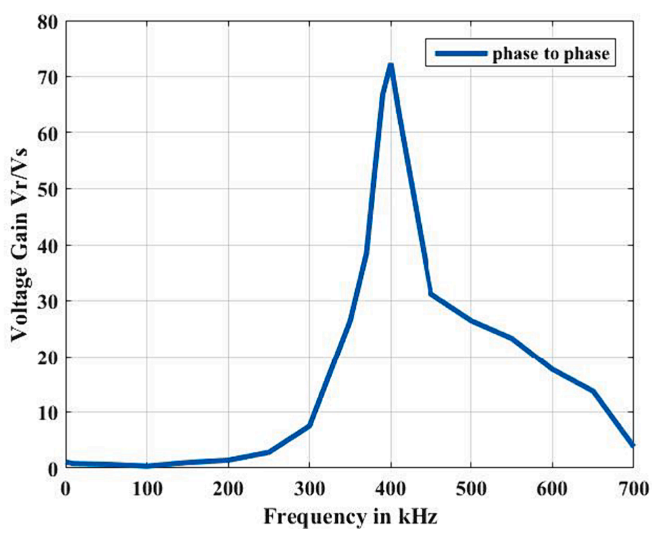

Fig. 4. Defining the communication channel of the distribution transformer.

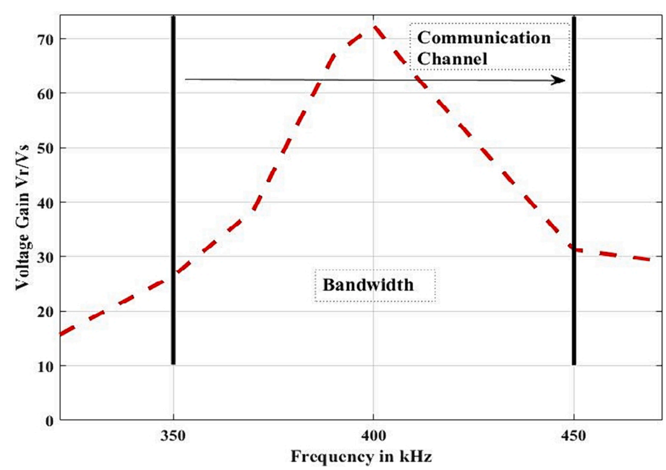

Fig. 5. Selected gap of transformer channel response.

the source to the secondary side of the distribution transformer.

6. Conclusion

PLC offers compatibility with multiple applications, ranging from residential home automation to industrial automation, smart grids, and intelligent transportation systems. The versatility and adaptability of PLC enable its integration into various domains, providing reliable and efficient communication solutions. The compatibility of PLC with different data types and protocols ensures seamless integration and interoperability within the respective application ecosystems. Additionally, the ability of PLC to coexist with other communication technologies and the availability of standardized protocols further enhance its compatibility across multiple applications.

Moreover, PLC offers numerous advantages, including the utilization of existing infrastructure, cost-effectiveness, wide coverage and penetration, reliability and stability, scalability and flexibility, easy deployment and integration, security, and compatibility with multiple applications. These advantages make PLC a compelling choice for organizations seeking efficient and reliable data transfer and communication solutions.

In this paper, a different PLC application is proposed and believed that it will be a core function of smart grid and remote metering applications. To achieve this goal two different modulation techniques (BPSK and QPSK) are proposed and compared to their efficiencies. Monte Carlo simulation method is used for the simulation transformer's AWGN channel performance.

In the future, several areas of study and research are expected to further enhance the capabilities and efficiency of PLC. Some of these future studies include:

- Noise Mitigation and Channel Modeling: Power lines introduce significant noise and interference, which can degrade the quality of the communication signal. Future research aims to develop advanced

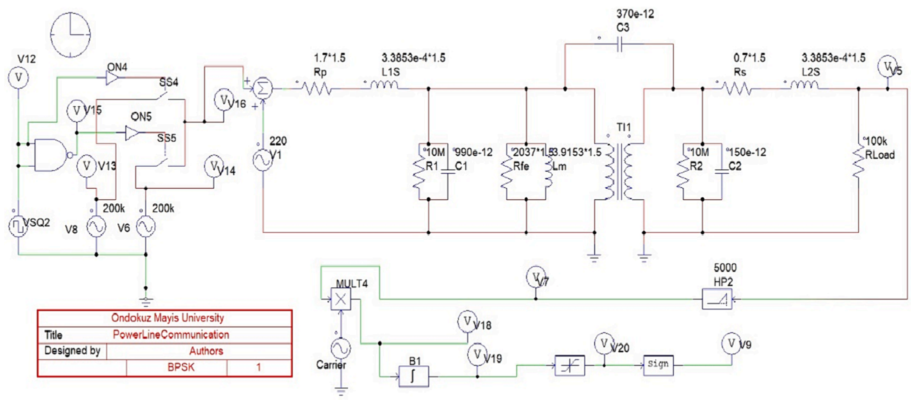

Fig. 6. Application of BPSK modulation technique.

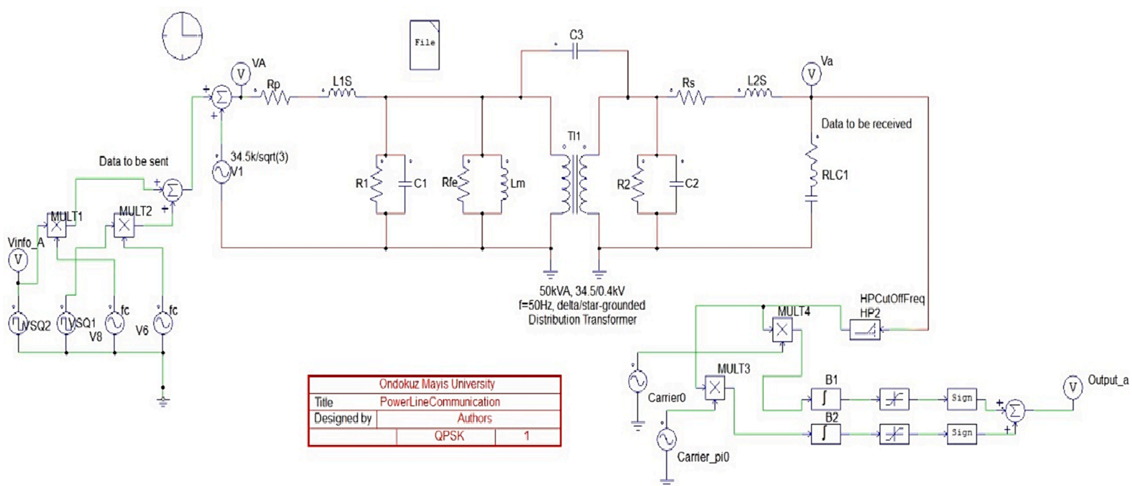

Fig. 7. Application of QPSK modulation technique.

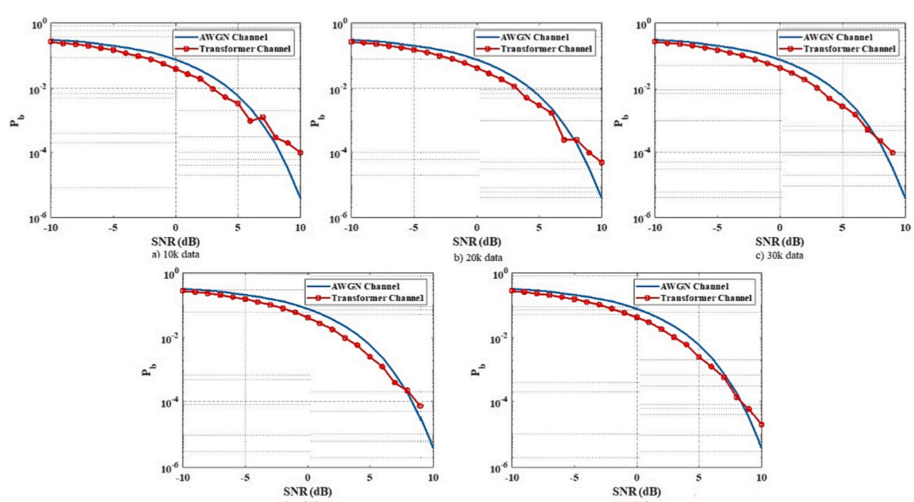

Fig. 8. Sending randomly selected data from source to the secondary side of distribution transformer using BPSK modulation.

noise mitigation techniques and accurate channel models to improve the reliability and performance of PLC systems.

- Higher Data Rates: Current PLC systems offer relatively lower data rates compared to other wired and wireless communication technologies. Future studies will focus on developing techniques to increase the data rates of power line communication, enabling support for high-bandwidth applications such as video streaming, real-time gaming, and high-speed internet access.
- Coexistence with Other Technologies: PLC systems need to coexist with other devices and technologies that share the power line network. The research will focus on developing interference mitigation techniques to enable seamless coexistence with existing

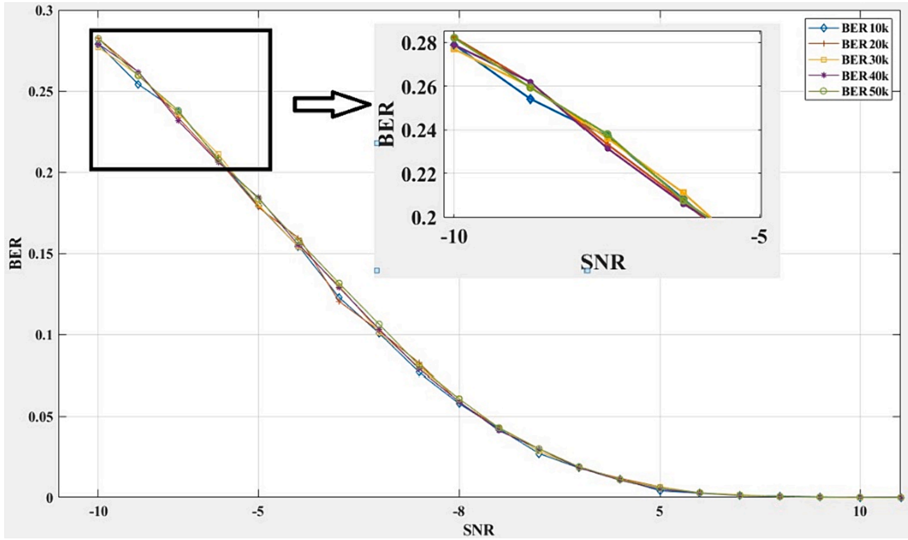

Fig. 9. BER values for BPSK data from 10 k to 50 k with respect to SNR.

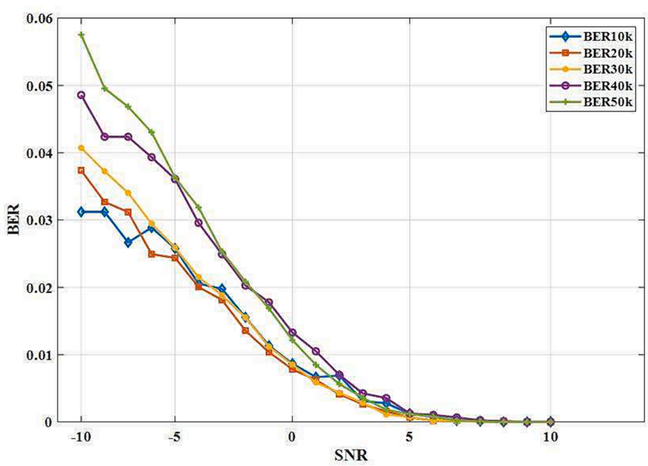

Fig. 10. BER values for QPSK data from 10 k to 50 k with respect to SNR.

power line devices, as well as with other communication technologies such as wireless networks and radio frequency (RF) devices.

- Standardization and Interoperability: To promote the widespread adoption of PLC, future studies will emphasize standardization efforts to ensure interoperability between different power line communication devices and systems. Standardization will enable seamless integration and compatibility across different manufacturers and service providers, fostering a more cohesive and interconnected PLC ecosystem.
- Security and Privacy: As PLC networks become more prevalent, ensuring security and privacy will be crucial. Future research will focus on developing robust encryption and authentication mechanisms to protect data transmitted over power lines from unauthorized access and interception.
- Integration with Renewable Energy Systems: With the increasing adoption of renewable energy sources such as solar and wind, future studies will explore ways to integrate power line communication with these systems. This integration can enable real-time monitoring, control, and optimization of renewable energy generation, facilitating better management and utilization of clean energy sources.
- Advanced Smart Grid Applications: Power line communication plays a vital role in enabling smart grid functionalities such as demand response, grid monitoring, and distributed energy resource management. Future studies will focus on developing advanced smart grid applications that leverage the capabilities of PLC to improve the efficiency, reliability, and resilience of the power grid. Moreover, these are just a few examples of future studies that are expected to shape the development and advancements in power line communication. As technology evolves and new challenges and opportunities arise, researchers and engineers will continue to explore innovative solutions to enhance the capabilities and applications of PLC.

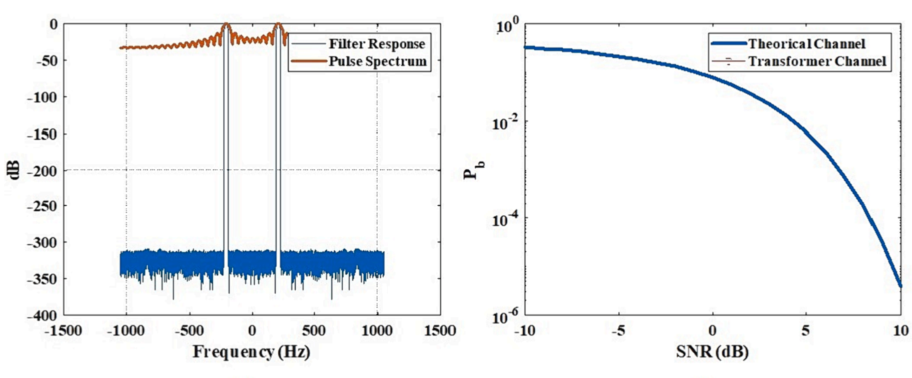

Fig. 11. Performance curve over sound data, a) filter response and pulse spectrum, b) theorical and AWGN channel.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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