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Review

Power line communication: A review on couplers and channel characterization

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Abstract: Powerline communication is gaining momentum with the rise of the smart grid, the Internet of Things as part of the 4th industrial revolution and associated applications such as transportation and energy efficiency. Coupling and channel characterization are essential parts of a power-line communication system. Therefore, understanding these components allows performance evaluation and prediction of the system. This paper presents an entire review of couplers and channel characterization modeling techniques used in narrow and broadband power-line communication systems. Types and applications of different couplers are presented; a review of different power-line communication channel modeling techniques and the fundamentals allows a clear understanding of factors influencing or affecting the signal propagation through the channel. The purpose of this review is to guide researchers and system designers looking for literature resources on couplers and channel characterization for power-line communication applications.

Keywords: power line communication; capacitive coupler; inductive coupler; resistive coupler; channel characterization; noise; broadband; narrow-band

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1. Introduction

The concept of power-line communication (PLC) consists of using electrical power cables or lines to transmit communication signals. Major George Squier of the US Army first implemented it in the 1910s. He transmitted an analog voice signal over a pair of power-lines. The signals were used by utilities in the operation of the distribution networks. In the 1930s, PLC technology was mature, allowing the transmission of telephonic signals over power lines [1]. A communication system for grid operation became more indispensable as the power network grew. Utilities have been using various communication systems, including PLC. The latter proved to be efficient and economical, as it uses preexisting power lines, decreasing its deployment cost. Nowadays, applications for power-line communication systems have widened with the emergence of the smart grid concept, where there is a need for constant communication for real-time monitoring and operation in energy management and network security [2].

Moreover, PLC systems are used in smart homes for broadband, voice and video communications [3–5]. They have applications in avionics, where power lines are used for data transmission, thus reducing the cable footprint on an aircraft [6]. Similar methods are introduced in the electrical vehicle industry [7,8].

A device called the coupler injects the communication signal into the electric power line or cables. Note that the power lines might be Direct Current (DC) or Alternating Current (AC) lines. The coupler blocks the main DC voltage from the grid and passes the communication signal for DC lines. In practice, the PLC transceiver signals are coupled to the power lines through the coupling device, which also has the task of filtering out power signals in the case of AC power lines and other noise.

PLC systems are classified according to their operating frequencies: Narrowband or Broadband. The narrow-band refers to the operating range of 5 kHz - 500 kHz, while the broadband ranges from 1.7 MHz to 30 MHz. Currently, various researchers are looking into increasing the frequency up to 500 MHz, increasing the data transfer rate and consequently widening the applications linked to high data transmission [9]. The ongoing research on PLC technology also focuses on coding, modulation, coupling and channel characterization. Coupling and channel components are key aspects of PLC systems. This study focuses on the literature on the past, present and future trends of coupling and channel characterization. The aim of this paper is to serve as a guide to researchers and PLC system designers by providing to them literature resources on coupler and channel characterization for power-line communication applications.

2. Coupling

The coupling is an essential part of power line communication; thus, there is a need to understand and improve it for a brighter future for PLC. The future of PLC depends mainly on how the Coupling Unit (CU) is designed, interfaced and coupled with a Power Grid and how it performs under a very noisy environment. There are six criteria by which PLC couplers can be classified: (1) The physical connection, (2) Voltage level, (3) Voltage type, (4) propagation mode, (5) frequency band and (6) number of connections. Figure 1 shows different types of PLC in each category. However, in this study, we will focus on the physical connection. It deals mostly with the communication signal integration, injection and extraction into and from the power line. Therefore, according to the physical configuration to connect to the line, there are four coupling methods: antenna, resistive, inductive and capacitive.

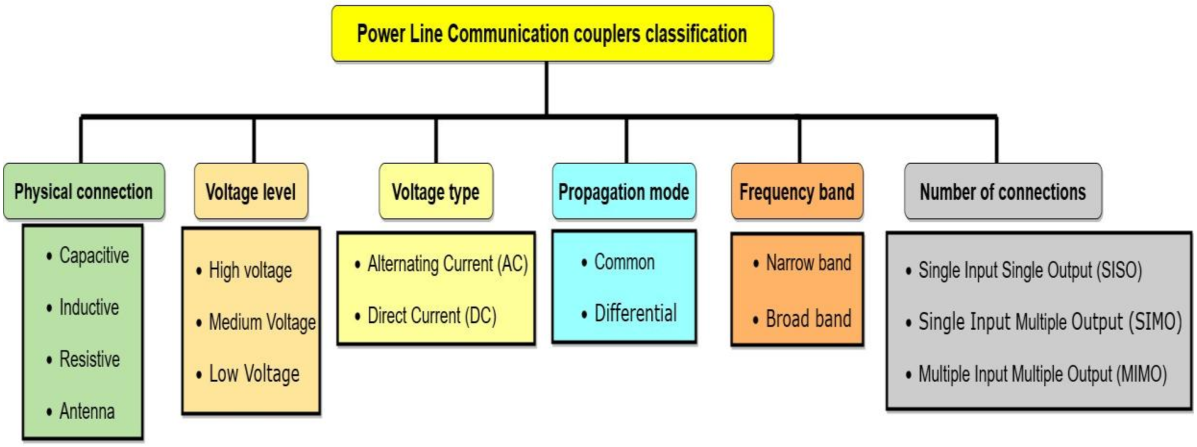

Figure 1. Classification of power-line communication couplers.

2.1. Antenna coupling

The antenna coupling method was first used in power line communication. It consisted of running a parallel wire or antenna alongside the power line to induce or extract the communication signals in the line. The antenna coupling method for power line communication was preferred in high voltage transmission lines due to its safety, because it does not have direct contact with the electrical power line. It uses air as dielectric insulation with low chances of progressive deterioration, as might be the case with air dielectric-based capacitors. The antenna coupling method has the advantage of having wires out in the open, easily accessible for inspection and maintenance. However, the Antenna coupling system is disadvantaged by the required extra stringing of wires at the substation that might require reinforcing the supporting structure or towers. According to [10], this disadvantage was why the antenna coupling was superseded by the capacitor coupling method, not the efficiency, as usually thought. Figure 2 shows the equivalent circuit model of an antenna coupler.

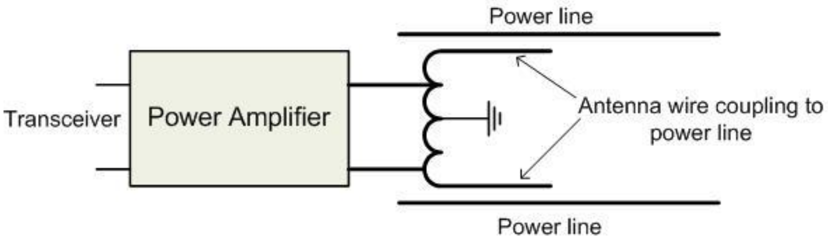

Figure 2. Antenna coupler model.

The antenna coupling method is again getting the attention of researchers focusing on PLC wireless systems [11,12]. [13] presents the straight power line antenna model, an analytical and numerical approach for solving the Pocklington integro-differential equation of induced current distribution by an antenna into an overhead line situated over a finite conducting ground. In [14], an investigation was made on interference effects on PLC communication where the building wiring system is used as an antenna. [15] presented a patented method for integrating a Wi-Fi antenna into a low-voltage (LV) distribution system wiring. The method was called an Integrated Long-Wire Dipole

Antenna (ILDA). Authors in [16] presented a contactless power line communication system. The presented system uses a cable as an antenna for coupling to the power line that carries and radiates 2.45 GHz Wi-Fi signals over a distance. The system with antenna coupling proved to perform well for a maximum range of 40 m.

2.2. Capacitor coupling

The capacitor coupling method is a sequel to the antenna coupling method due to its compactness and easy installation in a substation; the capacitive coupling method offers high power transfer among other PLC coupling methods or techniques [17]. In this method, the communication system or circuit is directly connected to the power line through the capacitor, as shown in Figure 3. Note that two types of coupling capacitors are used in PLC applications: transformer and transformerless capacitor coupling [18,19]. The transformer capacitive coupler is advantageous in galvanic isolation and protection against the surge that might affect the communication equipment or transceiver. This type of coupling is expensive due to the added cost of a transformer. It is usually used for AC circuits, but they are also found in DC systems [20,21].

In contrast, though economical, the transformerless capacitive coupling method does not offer galvanic communication circuit isolation from the power mains [22,23], thus making it less safe for the transceivers and the users of the communication equipment. To overcome the galvanic isolation issue of PLC transformerless capacitive coupling, [24] presented an opto-capacitive PLC coupling method, which offers full galvanic isolation to communication equipment from the power line.

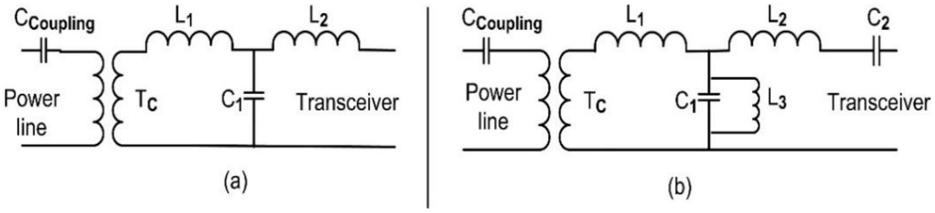

Figure 3. PLC capacitive coupling configuration: (a) Coupling through a transformer and (b) Coupling without a transformer.

The capacitor coupling method is primarily used in PLC high voltage applications for communication signal integration into the power lines [25]. [26] specified the essential characteristics of coupling capacitors in PLC, ratings and capacitor tests such as high voltage impulse withstand to determine the insulation capacity, thermal stability, etc. Table 1 provides an approximate list of currently available coupling capacitors for different voltage levels.

In [27], the feasibility of using a capacitor current-based coupling technique for PLC signal reception in the form of current is presented. Compared to classic PLC, the presented technique improves the PLC signal reception in the AC-DC converters during the charging period of the smoothing capacitor. However, it has a drawback in that the capacitor charging duration is short and dynamic; it depends on the capacitance of the filter and the load current. This affects the coupling performance. This drawback is addressed in [28], where the authors proposed a time diversity concept for couplers. The concept consists of an automatic switch between the PLC capacitor current-based coupling and the normal PLC voltage-based coupling.

Table 1. Commonly used coupling capacitors [25].

Voltage class (kV)	Coupling range (μF)	Voltage class (kV)	Coupling range (μF)
34	0.004-0.010	161	0.012-0.014
46	0.004-0.015	230	0.0009-0.010
69	0.003-0.015	287	0.0006-0.007
92	0.002-0.020	345	0.0005-0.006
115	0.019-0.020	500	0.0014-0.005
138	0.014-0.016	765	0.0023-0.005

PLC Capacitive coupling with Single Input Single Output for application in High Voltage transmission lines is discussed in [29]. The PLC coupler is designed for narrow and broadband PLC and is connected between the line and the ground. Note that two line-to-ground coupling schemes are used in narrow-band single and two-frequency resonant circuits. Figure 4 shows the implementations of both schemes.

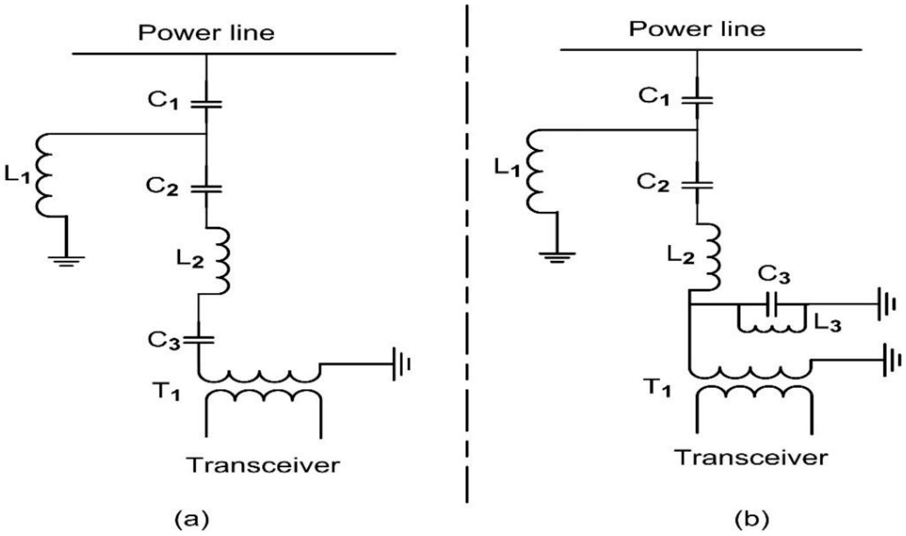

Figure 4. Capacitive coupling configuration for High Voltage lines: (a) narrow-band single frequency coupling configuration and (b) two-frequency narrow-band coupling configuration.

PLC coupling integrating capacitor and optoelectronics caught the attention of some researchers. In [29], a detailed model of PLC over a Medium Voltage network is developed and validated by an on-field test; capacitive coupling is used to interface the communication circuit to the power circuit on both sides of the line. A capacitive coupling for PLC is used in [30], where a new low-cost medium-voltage PLC coupler for a smart grid is presented.

The proposed coupling method makes use of the existing capacitor of the voltage detector installed in the medium voltage switchboard for PLC signal injection or extraction to and from the line. The design and characterization of the capacitor coupler based on a voltage detector for application in smart energy systems are presented in [31]. The capacitive coupling method is also used in [32]. In [30], a capacitor is used in the coupling diversity for the PLC interface to a networked Light Emitting Diode lighting system in a smart building context. A broadband opto-capacitive-based PLC coupler method is presented in [31]. The proposed method combines a capacitor and an opto-coupler to increase the safety of users and improve communication signal extraction.

2.3. Inductor coupling

Another method of physically coupling PLC circuits to mains is through inductors. The inductive coupler can be installed in series or shunt-in with the mains. Figure 5 shows both configurations of inductor coupling, and the shunt inductor coupling provides complete electrical isolation between the PLC circuits and the electrical power line or cables.

The inductive couplers work on the electromagnetic induction principle. The communication signal flowing through the electrical power line or cable is induced in the secondary coil of the coupler, in the case of serial inductive coupling, which is connected to the rest of the PLC circuits or transceiver for communication signal treatment. This process for serial inductive coupling is likened to the potential transformer method. In the case of shunt inductive coupling, a similar principle of electromagnetic field induction holds as in a current transformer. In the latter case, the installation does not require power service interruptions, as there is no electrical contact between the main power line and the coupler. The latter is just clamped around the power lines [32]. Figure 5 shows the configuration of PLC serial and shunt inductive couplers T_1 and T_2. They consist of magnetic coils wound around a magnetic material and the inductor output terminals connected to a PLC circuit. The inductive coupler might suffer from saturation in MV networks due to high current [33]. Various research studies have been done on mitigating the magnetic saturation that might affect the quality of the coupling [34–37].

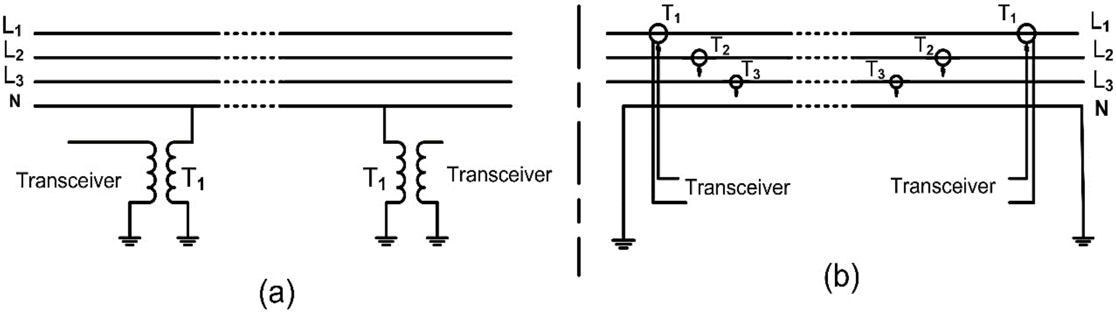

Figure 5. PLC inductive coupling configurations: (a) series inductive coupling and (b) shunt inductive coupling.

A high magnetic coupling coefficient is required from a shunt inductive coupler, also known as a non-invasive coupler, to have minimum signal injection loss and signal return loss. These are usually related to the properties of the magnetic material of the coupler current transformer like linearity, the maximum primary current transmissible and the phase error [37–41]. A clamp inductive coupling model for PLC application in medium voltage distribution is presented in [42]. An efficiency analysis based on the structure type of the coupler and the cable structure was performed; a mathematical model of the coupling associated with the Rogowski coil was developed, including the loose-coupling transformer model and the mutual inductance. The calculation and simulation results showed the effects of various coupler parameters on signal transfer. The model proved to be a good analysis tool for applying PLC in the intelligent distribution network. The performance of Rogowski coils-based inductive couplers for PLC in lithium battery traction was addressed in [43]. The authors proposed using a Rogowski-based inductive coupler for PLC in battery management due to its non-saturating effects, simplicity and light weight. The results show that using a Rogowski coils-based PLC coupler is a practical method in the lithium-ion battery packs management application of PLC.

Various research studies have focused on inductive coupling, as it is considered the best method of coupling for PLC due to the simplicity of installation and improved safety for users provided by the galvanic isolation between the line and the coupler circuits. [35] presented the characteristics of a nanocrystalline-based inductive coupler for contactless PLC application in an electric vehicle. The results showed that using a miniaturized nanocrystalline coupler reduces the amount of electrical wiring and, therefore, the overall weight of the electric vehicle. In [44], a nanocrystalline-based inductive coupler is used in an electric vehicle's experimental high voltage PLC application. The results show that high voltage power-line communication reduces wiring cable weight and allows a data transmission rate of 35 Mbps, enabling a successful real-time video transmission from the engine room to the trunk. [45] presented a feasibility study on using power-line communication to regulate an inductive power transfer in modern electronic systems and appliances; the inductive coupling method was used for data transmission over the lines. The performance improvement possibility of a coupled power line transfer (WPT)- power line communication system is investigated in [46]. The results show that a higher, wider band for communication is achieved. [47] presented a comparative evaluation of the effects of capacitive and inductive PLC couplers on the quality of bi-directional video transmission using broadband over PLC in mining.

2.4. Resistive coupling

The resistive coupling method is suitable for low-voltage narrow-band PLC system applications. Figure 6 shows a resistive coupling circuit as proposed in [48]. It consists of resistors configured as the voltage divider, a buffer, filtering and an amplification unit. The voltage divider reduces the incoming mains voltage signal to an acceptable level for the bandpass filter. The latter extracts the communication signal in the frequency range of interest, and it is fed into the amplifier. The amplified signal is processed by the analog to digital converter and subjected to further processing by the PLC transceiver. The resistive coupling is cheap and easy to implement, but it does not offer a galvanic isolation.

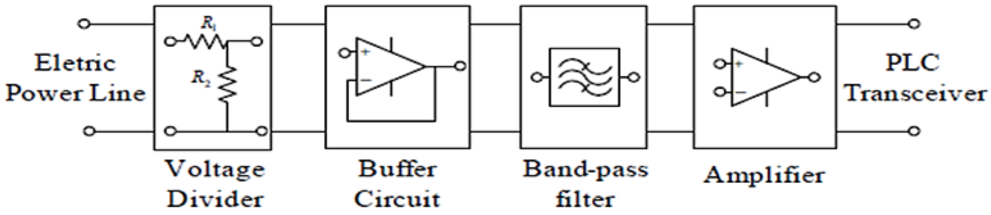

Figure 6. Resistive PLC coupler configuration diagram.

3. Channel modeling and characterization

Understanding the transmission medium or channel through which the signal travels is crucial for any communication system designer, thus the importance of channel modeling and characterization in the PLC system implementation. It provide the channel impact on the transmitted communication signal, allowing system performance prediction [49–52]. The channel modeling falls into the following categories: statistical, deterministic, parametric and field-based measurement modeling [53].

PLC channel characteristics and effects on the transmitted signal are described based on the transmission line model, as shown in Figure 7. Consider a power line from point a to point b, currying currents $I(a,t)$ and $I(b,t)$, at voltage levels $V(a,t)$ and $V(b,t)$. The parameters of the line are resistance per unit length R in (Ω/m), per unit length inductance L in (H/m), per unit length capacitances C in (F/m) and per unit length conductance G in (Ω^{-1}/m). The line effect on the transmitted signal is obtained from the high frequency equation (1) of the transmission line [54].

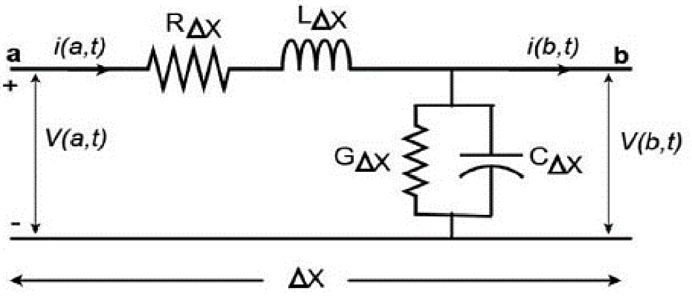

Figure 7. Transmission line model.

$$\begin{cases} -\frac{v(b,t)-v(a,t)}{\Delta x} = Ri(a,t) + L\frac{\partial i}{\partial t} \\ -\frac{i(b,t)-v(a,t)}{\Delta x} = Gv(a,t) + C\frac{\partial v}{\partial t} \end{cases} \tag{1}$$

Knowing that $v(a,t) = Re[V(a,t)]$ and $i(a,t) = Re[I(a,t)]$, equation 1 results in the following.

$$-\frac{dV}{da} = (R + j\omega L)\, I(a)$$

$$-\frac{dI}{da} = (G + j\omega C)\, V(a)$$

$$\begin{cases} \frac{d^2V(a)}{da^2} = (R + j\omega L)(G + j\omega C)V(a) = \gamma^2\, V(a) \\ \frac{d^2I(a)}{da^2} = (R + j\omega L)(G + j\omega C)I(a) = \gamma^2\, I(a) \end{cases} \tag{2}$$

γ = the coefficient of propagation, and it is calculated using equation 3:

$$\gamma = \sqrt{(R + j\omega)(G + j\omega C)} = \alpha + j\beta \tag{3}$$

where α is the attenuation portion, and β is the propagation portion.

Then,

$$V_O = V_O^{+e^{-\gamma a}} + V_O^{-e^{\gamma a}} \quad \text{and} \quad I_O = I_O^{+e^{-\gamma a}} + I_O^{-e^{\gamma a}}. \tag{4}$$

From the above equations, the line characteristic impedance is calculated as in [55].

$$Z_L = \frac{V_O}{I_O} = \sqrt{\frac{(R+J\omega L)}{G+j\omega C)}} \tag{5}$$

The line per unit characteristic impedance parameters are given by the following formulas [56].

$$R = \frac{1}{\pi\, r}\sqrt{\frac{\pi f \mu}{\sigma}} \tag{6}$$

$$L = \frac{\mu}{\pi}\cosh^{-1}(\frac{D}{2r}) \tag{7}$$

$$C = \frac{\mu\varepsilon}{\cosh^{-1}(\frac{D}{2r})} \tag{8}$$

$$G = \frac{\mu\sigma}{\cosh^{-1}(\frac{D}{2r})} \tag{9}$$

The above equations show that the signal attenuation is a function of the line's characteristics, such as the frequency and the length of the transmission line or the channel and the configuration. Note that the impedance of the line changes as the loads are connected or disconnected [57,58]. This creates a mismatch in impedance and reflections along the line branches [59–61]. Thus, it is more challenging to develop a characteristic channel model for PLC in low and medium-voltage networks than in high voltage, where point-to-point networks are usually found. The channel modeling allows the evaluation of PLC channel transmission capacity and the system performance [62]. Many researchers have developed various PLC channel model methods and transfer functions for different applications and environments [63–66].

[67] presented the use of power line communication technology for data exchange over a DC bus in a spacecraft. An analysis of a channel characterization and an electromagnetic compatibility evaluation of a PLC link for low-speed interconnection with sensors were performed. The modal analysis method is used for channel performance estimation. Asimulation of coupling for onboard PLC for a spacecraft power bus, using Simulation Program with Integrated Circuit Emphasis (SPICE) simulator,is presented in [68]. In the latter, a DC bus channel characterization was performed for transmission performance evaluation. Note that simulation and emulators are cost-effective methods for channel model validation. In [69], an easily configurable, practical and circuit area-efficient low voltage broadband PLC channel simulator is presented. It is implemented and validated on the FPGA platform. In [70], a channel emulator for broadband, multiple input multiple output PLC is shown. The emulator is FPGA based, allowing very reliable and reproducible testing results for PLC channels, modem and couplers. The results of the physical validation of the emulator are presented in [71]. A narrow band PLC channel emulator for smart grid application is presented in [72]. It allows overcoming the difficulties of the verification process of a PLC system.

Ultra-Wide Band transmission (UWB) channel characterization and simulation are presented in [73]; the paper investigates the concept of indoor application of UWB PLC transmission. The results show that a high data transmission rate is feasible in the range of 50–500 MHz. However, early study results in [74] suggested a wider frequency band of 50–800 MHz for high data rate transmission over the power-line as a feasible range. In that study, the characterization of household power-line for UWB communication and experimental channel testing emphasized radiation, signal attenuation and dispersion.

Various research studies have also focused on broadband channel characterization for different PLC applications. [75] presented a method for developing a model for the transfer function of a power line communication network. The derived model uses the reflection and transmission factors and considers all connected loads and the line distance. A comprehensive study on channel modeling of broadband communication over low voltage networks is presented in [76]. The ABCD two-port model of the low voltage distribution network is described, and the related transfer function is derived. A channel characterization of broadband power-line communication based on transmission line theory is presented in [77]. The channel characteristics are derived using transmission line theory, reflection theory and radiation loss of a long line, and the transfer function for a theoretical two-wire PLC is developed. In [78], skin effect and proximity effects impact low voltage power-line broadband communication channel parameters. An approach for attenuation evaluation for a multipath model for broadband power-line communication is presented in [79], and the channel transfer is developed based on the proposed approach. Characterization and modeling of various power-line communication channels are presented in [80]. The authors also proposed an approach for channel modeling for broadband power line communication in low voltage radial network topology. The broadband PLC on the customer side and its interaction with the network caught the attention of the researchers. Thus, in [81], the authors investigated the impact of a fundamental characteristic of a power distribution network on the client premises on broadband PLC. The results showed that the model for average attenuation fails to represent the character of a broadband PLC system; rather, a multipath model proposed by the authors is much more suitable for Broadband Power Line communication channel characterization on the customer side.

PLC application in houses is growing with energy efficiency, house automation and the internet of things [82]. Thus, the research on indoor PLC is gaining attention, as the channel characterization for indoors is complex due to the dynamic nature of its impedance and the topology of the network [83]. An analysis of broadband communication over the indoor PLC channel is presented in [84]. The authors developed an ABCD-based matrix to evaluate the channel transfer functionand to investigate the impact of network topology variation and the system's performance. The paper provides a detailed analysis of the impact of the channel capacity regarding the channel size and its overall impedance. In [85], channel modeling and estimation for indoor power-line communication are presented. The authors used Zadeh's series expansion to model the power-line channels, and various channel parameter estimation methods are presented. In [86], a lattice approach for high-speed indoor PLC channel modeling is presented. The method regards the power line network as a lattice structure, and the proposed model is validated against the experimental measurements. Broadband PLC channel performance for different topologies is presented in [87]. Different topologies of indoor network models are developed, and transfer functions for power-line channels are derived. A MatLab environment is used for simulation.

Among the PLC deployment options or environments is outdoor deployment. It is deployed over a short-range network in rural, urban and suburban areas and isolated in small distribution networks [88]. A characterization of NB-PLC for automatic metering in a smart grid in an urban environment is presented in [89]. The paper also evaluates the performance of the NB-PLC in wireless technologies for the frequency ranges of 9–500 kHz and 865–870 MHz

An analysis of outdoor power line communication is presented in [90]. The authors made outdoor measurements on the distribution network to obtain the channel characteristics. The results converge with the statistical model theory, and the delay spread of the channel is evaluated. [91] presented a noise characterization and modeling of the PLC line. In the study, various noises in the network are characterized, and types of noise, their sources and their potential impacts on the channel are identified. White noise, colored noise and impulse noise are identified in the PLC channel, allowing design of adequate mitigation measures. A narrow-band noise characterization and channel capacity of the network in France are presented in [92]. Various sites are used for experimental measurements of low voltage NB-PLC channel frequency and estimation of theoretical channel capacity.

Knowledge of the channel's noise characteristics is essential in PLC system design. The noise model and estimation are part of the channel characterization, allowing the performance evaluation. Many researchers have focused on noise in the context of PLC. This paper presents some of the work found in the literature. In [93], the characterization of time variation of power-line frequency response is presented simultaneously with impulsive noise. The authors established a correlation between the impulsive noise and variation in channel frequency response by using a statistical analysis of variation. The impulse noise mitigation method in the power-line channel is presented in [94]; the technique uses a subcarrier coding of the OFDM–MFSK scheme. It uses the permutation code in multiplexing and processing, which improves the bit error rate performance. [95] presented a capacity analysis of an NB-PLC system with background and impulsive noise. Gaussian noise and the Laplace distribution method characterize the background and impulsive noise. The Gaussian method is also used in [96] for capacity analysis of narrow-band PLC channels operating in the range of 3 kHZ – 500 kHZ in the presence of impulsive noise. In [97] an analysis of channel characteristics of impedance, noise and signal attenuation in power-line communication is presented, and a comparative analysis of two existing power-line channel models is conducted.

Overhead lines are used mainly in electric power transmission and distribution networks. Although primarily dominated by overhead lines, the distribution networks have a fair share of cables. PLC is gaining the attention of researchers for its application in Low voltage distribution networks in the context of smart grids [98]. An approach to study and simulate signal transmission characteristics over low voltage is presented in [99]. Two wire-based model and the chain parameters matrices methods are used for transfer function derivation. An analysis of channel behavior in response to network parameter variation is presented. The results show a correlation between the transfer function and the network configuration. In [100], a PLC channel characterization is presented for a distribution network based on measurement. Mathematical models of the spectral density of the power for the two types of noise, the background and the impulsive, are developed. In [101], a Markov chain method is proposed to model a PLC channel in a low voltage network. [102] presented an approach for modeling a low voltage broadband PLC channel using graph theory. PLC channel modeling for a three-phase distribution line for an intelligent system is presented in [103]. The model uses three phases and has the advantage of considering the source and load admittance matrices, and the model is validated by measurement. [104] presented an investigation on the impact of characterization of power loads on statistical modeling of an indoor power network. The bandwidth range of interest is 100 kHz – 50 MHz, and the results show a marginal load characterization effect on the accuracy of a statistical model channel in the frequency range above 20 MHz. In [105], the statistical modeling of hybrid PLC-wireless channel characteristics is discussed. The authors provide an excellent statistical model that facilitates a full apprehension of the hybrid PLC-wireless channel.

In addition to the channel characterization, modulation is one of the key aspects in the development and application of PLC. The PLC signals are subjected to hostile dynamic channel conditions not found in other communication channels, thus the need for an appropriate selection of the modulation scheme. [106] highlighted some aspects to consider in selecting a modulation scheme: susceptibility to various noises, the time-varying nature and frequency selectivity of PLC channels and the limitation of the transmitted power over PLC due to electromagnetic compatibility. The modulation methods usually used in PLC are single carrier, spreading spectrum and Orthogonal Frequency Division Multiplexing (OFDM) [107,108]. The single carrier modulations are simple to implement and are adopted in narrowband. However, they are not appropriate for broadband. The spreading spectrum modulation method was initially developed for military applications to resist intentional frequency interference. This characteristic is used in PLC applications to prevent frequency fading caused by multipath effects [109]. The OFDM method is used for high speed broadband PLC, as it has a great spectral efficiency [110]. Compared with other modulation methods used in PLC, OFDM presents the highest transmission rates and is the most suitable modulation method for PLC applications [111]. ITU-T-G.9903 regulates the OFDM modulation method in the CENELEC band standard. [112] presented various PLC standards and their relevant modulation methods.

4. Conclusions

A review of power-line communication research focusing on couplers and channel characterization has been presented. The coupling is essential to the power-line communication system and the transmission channel. Understanding the channel or medium through which the signal travels is critical to any communication system designer. It allows the estimation and the prediction of the performance of the transmission and reception operations and the quality of the signal, thus allowing the development and improvement of methods.

In this paper, the classification of the coupling methods is presented. It is based on various criteria such as voltage nature, voltage level, propagation mode and physical connection of the coupler. Various research studies on the couplers have been presented, including prosand consand each type's current and future applications.

Channel characterization theory is provided to explain factors and parameters that affect the communication signal over the power line. Past, current and future trends in the field have been presented. Different methods and techniques used for mathematical models for channel characterization in narrow and broadband frequency ranges have been presented. The current challenges to be addressed by future research are highlighted.

Conflict of interest

The authors declare that there is no conflict of interest in this paper.

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