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Current state of communication systems based on electrical power transmission lines

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Abstract

Power line communication technology is a retrofit alternative technology for last mile information technology. Despite several challenges, such as inadequate standards and electromagnetic compatibility, it is maturing. In this review, we have analysed these obstacles and its current application status.

Keywords: Electrical power lines, Power line communication (PLC), Power line networks, Noise, Channels, Modulation

Introduction

Indeed, advancements in communication engineering and technology have brought in revolution in the telecommunication industry. One great impact has been in information and service delivery during the last decades of the twentieth century to date. This is due to the high demand for information created by the huge human population. Better methods and channel models for signal transmission have been researched and developed. For instance, fibre optics has provided waveguide for numerous services at higher speed while inheriting other advantages such immunity to electromagnetic interferences amongst others [1, 2]. Despite all the positive attractions towards fibre communication, it is expensive to install and it is limited to certain areas. That is, remote, rural and mountainous areas. This has necessitated the search for alternative information transmission methods. Power line communication (PLC) is one such alternative.

Power line communication technology is the basically a technology that uses pre-existing and installed electrical power cables for transmission of information [3–6]. Traditionally, such electrical lines were designed exclusively for distribution and transmission of electricity at lower frequency. This frequency varies from country to country, mainly, 50 Hz or 60 Hz. Upon generation of electricity, it is distributed and transmitted through different voltage network. Firstly, electricity is transmitted over high voltage lines, then distribution is done over medium voltage lines, and lastly, it is converted/scaled down using transformers for the end-user consumption in the low-voltage lines. Figure 1 gives summary of PLC structure. This technology is therefore retrofit and economically cheaper compared to other methods. There is no need for new cable installations. Secondly, electrical power network is the most developed, covers large areas and

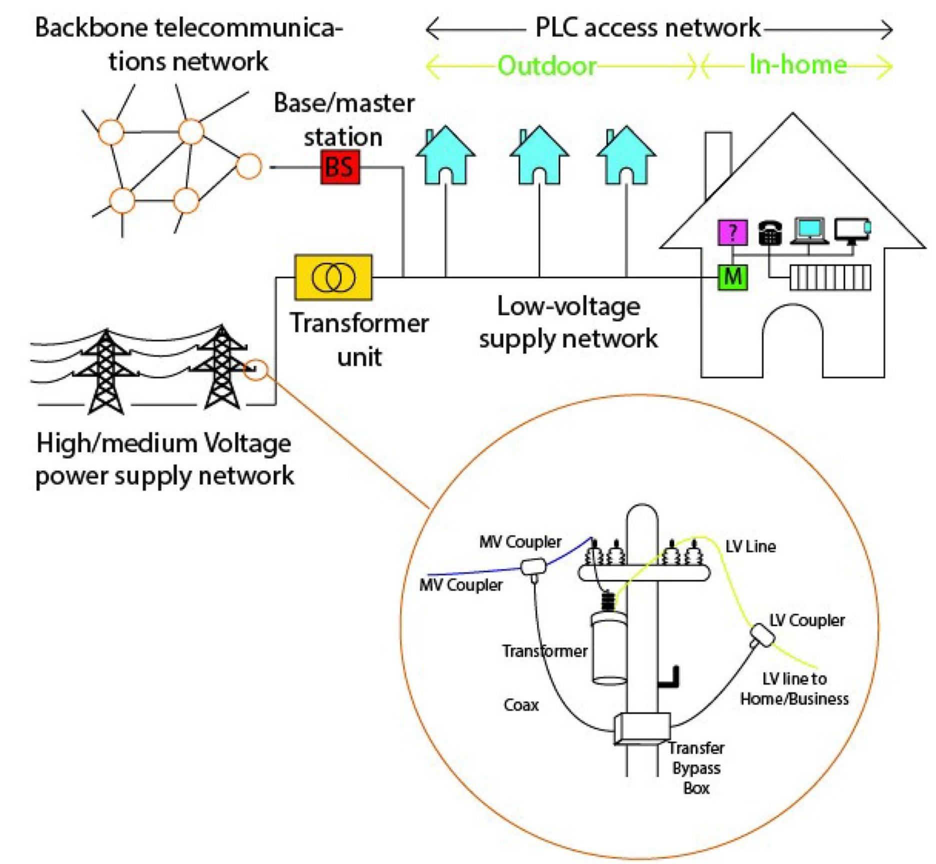

Fig. 1 Structure of power line communication network

reaches many homesteads. At distribution lines, they are majorly used for the control signals, remote data acquisition and IP telephony services [7].

Power line communication is divided into three categories, namely ultra-narrowband, narrowband and broadband as summarised in Table 1. The first two are commonly grouped together and termed as narrowband PLC. We will characterise these categories in the next section in details.

Classification of power line communication

The initial idea to use electrical power line for communication purposes was first put foward in the early 1900s. Schwartz in [8] gives comprehensive history regarding the technology. In the paper, PLC evolution in upto the early 2000s is also reviewed. According to [9], we have three categories of PLC as mentioned in the previous section. They are classified based on frequency band of operation and application areas. In Table 1, we give a brief summary of each class. Each category varies in application areas. For instance, ultra-narrowband PLC has been applied in automatic metre reading technology, while the second type has found its application in advance metre reading [10], electric vehicles [11], smart grid [9, 12] and street lighting [13, 14].

Broadband PLC has penetrated to high-speed internet access and home area network applications including audio, HDTV, online gaming and others in [17, 18].

PLC regulation standards

For universal functionality, there is need for proper standards to regulate communication quality and as well as to cater for minimal, if not zero, interference to human health. In telecommunication, such standards aid in designing an optimal communication system. The parameters that require governing and continuous check include signal-to-noise ratio (SNR) and bit-error-rate (BER). There has been an ever-rising interest in PLC technology in the last two decades. Therefore, researchers and non-governmental bodies have come up with set of rules and requirements to improve optimality and interoperability. This is of course to make electrical power lines more compatible and secure for transmission of different varieties of signals.

Internationally, the following organisations are responsible for setting and governing standards in the telecommunication industry; International Telecommunication Union (ITU), European Committee for Electro-technical Standardisation (CENELEC), International Electro-technical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), International Organisation for Standardisation (ISO) and lastly, Federal Communication Commission's (FCC). All these organisations have set standards for both broadband and narrowband PLC. Nonetheless, ITU favours the latter to be implemented within 3–490 kHz frequency for low speed transmission as mentioned in Table 1.

In order to work efficiently, CENELEC has several internal groups performing specific tasks. For instance, EN50065-1 is focussed on general requirements, frequency bands and electromagnetic disturbances for signalling on low-voltage electrical lines. EN50065-1 has subgroups which deal mainly with narrowband PLC, whereas EN55022 standard works on high-speed PLC in the spectrum of frequency between 150 to 500 kHz. While IEEE 1901.1 standard focuses on access communication systems as patented by IEEE. IEEE 1901.1 is designed for control transmissions of frequencies less than 15 MHz in smart grid applications [3, 16] and [references therein].

These standards also specify signal coding and modulation techniques. IEEE 1901.2 is a revised version of the first one that advocates for use of Reed Solomon (RS) and convolutional codes (CC). The latter is also compatible with Internet Protocol version 6 (IPv6) [18]. ITU and

Table 1 Categories of PLC technology

Type of PLC	Features	Related works
Ultra-narrowband	Frequency: 0.3–3 kHz Designed for single way communication links Data rate: Approx. 100 bps	[8, 15]
Narrowband	Frequency: 3–500 kHz (Europe) 10–490 kHz (USA) Designed for in-door communication links Data rate: Approx. up to 100 kbps	[15–17]
Broadband	Frequency: 1.8–250 MHz Designed for in-home links Data rate: Approx. up to 200 Mbps	[3, 6, 15–17]

Table 2 Regulator standards for narrowband PLC and relevant modulation methods

Standards	Modulation method	Related works
IEEE P1901.1	OFDM	[19, 20]
IEEE P1901	OFDM	[19, 21]
IEEE P1901.2	PSK & QAM (subclasses)	[19, 22, 23]
ITU-T G.9904	OFDM	[19, 24, 25]
ITU-T G.9903	OFDM	[19, 25, 26]
IEC61334	S-FSK	[19, 27–30]
G3-PLC	OFDM	[19, 31, 32]
ISO/IEC 14,908–1	BPSK	[19, 28, 33, 34]
PRIME	OFDM	[19, 31, 35]
ANSI/IEA 790.1,2	BPSK	[19, 36]
MAX2990	OFDM	[19, 37, 38]
STM7580	BPSK	[19]

Table 3 Regulator standards for broadband PLC and relevant modulation methods

Standards	Modulation method	Related works
KNX	S-FSK	[18, 19]
HomePlug 1.0	D4PSK	[19, 39]
HomePlug AV	BPSK, 4PSK, QAM & subclasses	[19, 40]

IEC have also contributed widely in developing some of these standards for narrowband PLC. Tables 2 and 3 provide summary lists of regulatory standards with regard to electrical power line communication technology and respective modulation techniques.

Challenges facing PLC network

Electrical power supply networks do offer an economical opportunity to realise info-communication network at no extra cost of laying new communication cable lines. They also cover large areas thus increasing the size of communication network.

However, electrical lines are by design not meant for communication purposes. Such lines have unconducive features for transmission of signals. At the same time, power cables are the most asymmetrical network with many irregular connections extending between end-users and communication backbone lines [17, 41]. Continuous connection or disconnection of electrical appliances, such as, all switching changes, may change the topology [41].Each load switched and connected to the network operate at varying frequencies thereby injecting noises and imbalance impendance. Noise is discussed in the next section.

Güzelgöz et al. in [42] have comprehensively compared wireless and PLC transmission channel. From their comparison, it is evident that PLC is characterised by multipath propagation. These paths are caused by the presence of reflection points with different characteristic impedances. In [43], other factors that affect signal transmission such as frequency- selectivity of PLC channel, mismatched connections and branches have been reported.

Attenuation which increases with frequency is another factor that hinders full exploitation of PL for communication use. Attenuation in this case depends on the length of branches, the material of the line and varying characteristic impedance too [44], and [references herein].

Electromagnetic compatibility is another challenge. From Maxwell's equation and electromagnetic theories [45, 46], and [references herein] electrical power lines, by extension PLC, act as antenna that excite electromagnetic waves. Therefore, use of frequency spectrum ranging to 30 MHz which is reserved for radio communication may be interfered with by power line communication networks. As discussed under standards, there regulations have been set to minimise PLC electromagnetic interference on other services. Additionally, electromagnetic compatibility restrictions limit transmission power which in turn leads to low SNR at the receiver. Works on the latter are also ongoing.

The other major factor that degrades signal transmission in PL channels is non-Gaussian noise. This noise will be discussed in a section below. Before that, we describe PLC channel briefly.

PL transmission channel

In both [42] and [43], and [references herein] have compared power line communication channel as a multipath transmission medium. This is because of numerous reflection points, discrete and mismatched electrical loads in the PLC network. The channel load is either varying periodically or aperiodically due to connection or disconnection of electrical loads at varying times.

Understanding the channels behaviour is very vital in designing communication systems. Therefore, engineers and researchers apply channel models in order to characterise PLC transmission channel. Generally, there are two models: bottom-up and up-bottom approaches [43] and [references herein]. These approaches are iterative. Their approach includes both measurements and CAD simulations. Both approaches are either applied in time or frequency domain. The bottom-up model approach involves the use of mathematical model to define electrical power line channel. Model's parameters are calculated followed by simulation. To validate simulation results, measurements must be carried. The difference is that, the second approach starts with measurements. Thus, there is need for comprehensive information of the network and its physical topology. It also requires knowledge on impedances and features of cables. Up-bottom approach is practical and realistic. It is therefore the frequently used model by communication engineers. Mathematical models for both approaches are available in [19] and [references herein] for the reader to explore.

Berger et al. in [5] introduce the concept of MIMO PLC model. This is another technique that can be used to study the channel's feature in order to improve PL communication system's performance. Intensive studies of various models are focussed on possible exploitation of adaptive filters and scheduling, development of efficient PLC code, widening the bandwidth amongst others. Other models of study are mentioned in [47].

Noise in PL communication system

This noise can be defined based on its magnitude, origin and its representation main in time domain. Electrical power networks are heavy loaded in the so-called "last mile" and in-door areas. At these points, electrical appliances are the main source of noise in PL systems.

Noise in PL communication systems is non-Gaussian as opposed to traditional data communication channels which can be expressed in terms of additive white Gaussian noise [48, 49], and [references therein]. Several researches have grouped noise in PLC as background noise and impulsive noises. Background noise is subdivided into coloured background and narrowband noises, while impulsive noise, namely periodic asynchronous impulsive noise to the main lines frequency, periodic impulsive noise synchronous to the main lines frequency and aperiodic impulsive noise. The sources and forms of these noises have been widely studied and documented in [19] and [references therein]. Figures 2 and 3 show PLC system and noise in the channel.

Modulation techniques for PLC systems

Impulsive noise has great negative effect on transmitted signal. Therefore, in order to combat its effect multicarrier modulation techniques such as OFDM have superiority over single-carrier types.

Hrasnica et al. in [17] and Guzelgoz et al. in [42] have detailed explanations how other modulation used in wireless communication can be applied in PL communication system. Such modulation techniques include frequency hopping of spread spectrum family and random packet modulations. All these modulation techniques advocate for interleaving that spreads bit and symbol errors [50], and [references herein]. There is need though to keep guard with regard to intercarrier interferences.

Coding techniques such as turbo codes [51] and Solomon Reeds amongst others are also used to improve channel capacity. In [19], a brief and clear explanation on modulation and coding techniques has been presented. In Tables 2 and 3, recommended modulation techniques used in PLC are presented. In Table 4, we tabulate history of OFDM which has shown resistance to the effects of impulsive noise.

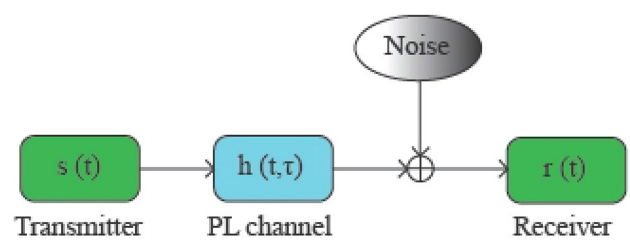

Fig. 2 PL Communication system

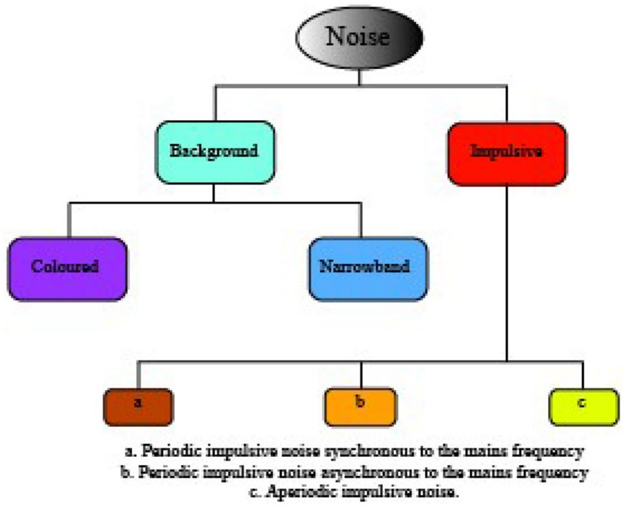

Fig. 3 PL Communication noise

Table 4 History of OFDM

Year	Description	Related works
1966	Proposal of the first OFDM. This was for fading communication channels	[52–54]
1967	Multicarrier systems	[53–55]
1970	OFDM is patented	[53, 54, 56]
1971	First application of DFT in OFDM	[53, 54, 57]
1980	OFDM is applied in telephone networks	[53, 54, 58]
1985	OFDM studies in mobile communication	[53, 54, 59]
1987	Used in digital broadcasting	[53, 54, 60]
1991 & 1994	Report and standard for ADSL and HDSL	[53, 54, 61–63]
1995	First standard for OFDM-based digital broadcasting system	[53, 54, 64]
1996	WLAN standard	[53, 54, 65]
1997	DVB-T standard	[53, 54]
1998	VDSL and BRAN standard	[53, 54]
1999 & 2000	IEEE 802.11a & 802.11g WLAN standard	[53, 54]
2003	Wavelet-OFDM for high-speed PLC	[53, 54]
2004	IEEE 802.16 WMAN, 802.11n next generation WLAN and 802.15.3a MB-OFDM	[53, 54]
2010	Performance comparison between wavelet-OFDM & filtered-OFDM	[53, 54]

Conclusion

As human population continues to increase, the thirst and demand for data information and education will always be on the rise. The emergence of COVID19 has also put pressure on the existing communication systems as many organisations shift to "work from home". This calls for alternative signal transmission technology. Electrical power lines for communication have proven to be this option. With roughly 80% of the world population connected to the electric grid, this technology ready infrastructure to connect millions to info-communication network for business, education and other purposes. Thus, geographical communication coverage is increased. Despite the tremendous work done in both research industries and universities, there is need for more to be done to improve this technology.

In order for PLC to reach optimal maturity and mass implementation, the challenging obstacles discussed above must be tackled scientifically, properly and effectively. Additionally, there is need for adequate research funding and implementation of national regulation standards to comply with the international ones for uniformity across the globe. The latter issues affect developing countries such as Kenya and Türkiye.

In this paper, we have provided a detailed overview on the current state of PL Communication. We have summarised classes of PLC, regulation standards, transmission channel models, noises and tabulated modulation techniques. Although this field of research is maturing slowly and is fairly recent, it has become a promising one for near-future applications especially in Access Mode "Last mile" implementation. We hope this work will motivate researchers further to advance the penetration of PLC technology in developing countries' remote areas where electricity access is available but with rugged terrains.

Abbreviations

PLC: Power line communication; ITU: International Telecommunication Union; CENELEC: European Committee for Electro-technical Standardisation; IEC: International Electro-technical Commission; IEEE: Institute of Electrical and Electronics Engineer; ISO: International Organisation for Standardisation; FCC: Federal Communication Commission; RS: Reed Solomon; CC: Convolutional codes; IPv6: Internet Protocol version 6; CAD: Computer-aided design; MIMO: Multiple-input and multiple-output; SNR: Signal-to-noise ratio; OFDM: Orthogonal frequency division multiplexing; BSPK: Binary phase shift keying; QAM: Quadrature amplitude modulation; FSK: Frequency shift keying; DFT: Discrete Fourier transform; KNX: Konnex protocol; WLAN: Wireless local area network; PL: Power line; S-FSK: Spread FSK.

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Authors' contributions

The details of contributions of the authors in the present works are as follows: (a) AN contributed to the literature collection and manuscript preparation. (b) İHÇ contributed and edited the manuscript. Finally, all authors read and approved the final manuscript.

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Declarations

Competing interests

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