Impulsive noise reduction techniques in power line communication: a survey

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Abstract: Power line communication (PLC) is a technology that permits data transmission using the electrical networks. In the last few years, research in the area of efficient wired home-networking services and smart grid has received a great interest thanks to the already-existing electrical networks and the ubiquitous sockets (outlets). However, the power line channel presents a challenging task and provides drastic medium for multimedia (audio, image and video) transmission. In fact, over the last decades, there has been an intense research in the area of impulsive noise reduction in PLC environments and numerous error-mitigation strategies have been proposed, thus the need for such a broad survey. To this end, this paper presents a comprehensive overview, with major emphasis on identifying strengthens and weaknesses of the state-of-the-art techniques, and discusses some challenges and future research directions thorough consolidation of related works on PLC signal protection strategies against impulsive noise effects.

Keywords: power line communication; PLC; wired home networking services; smart grid; multimedia transmission; electrical networks; power line channel; impulsive noise reduction; error-mitigation strategies.

Reference to this paper should be made as follows: Laksir, S., Chaoub, A. and Tamtaoui, A. (2019) 'Impulsive noise reduction techniques in power line communication: a survey', *Int. J. Autonomous and Adaptive Communications Systems*, Vol. 12, No. 2, pp.146–186.

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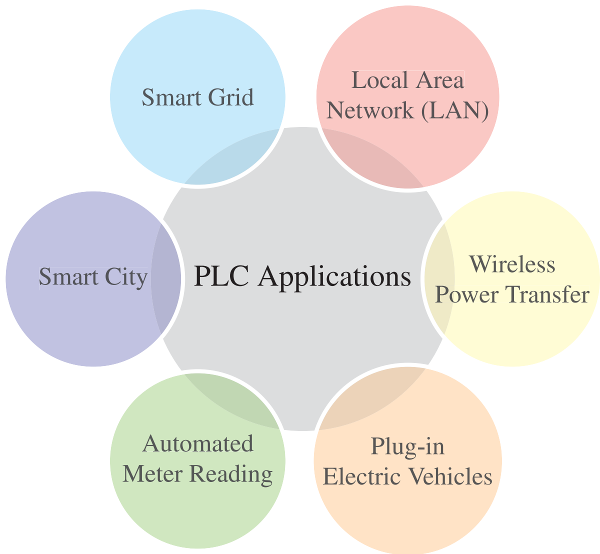
This paper is a revised and expanded version of a paper entitled 'Impulsive noise reduction techniques in power line communications: a survey and recent trends' presented at MoWNet'18, Tangier, Morocco, 20–22 June 2018.

1 Introduction

Power line communication (PLC) field is gaining ground in the commercial and domestic market for both indoor and outdoor contexts owing to its cost-effective usage and its faster data rates (Gotz et al., 2004; Hrasnica et al., 2004; Pavlidou et al., 2003). Unlike traditional power lines that carry the flow of energy from the power station to the final customers, PLC brings a paradigm shift as a well regarded technology that helps to deliver several content formats simultaneously with the electric power using the existing power distribution infrastructures. In fact, the use of the electric power grids already installed and the ubiquitous outlets are two revolutionary paradigms of the modern PLC technology, which can provide multimedia (audio, image and video) transmission capabilities using power supply networks.

The last decade have experienced increased deployment of the local area networks (LANs) PLC in buildings and offices to enjoy high-speed Internet and its related services (Galli and Logvinov, 2008). Figure 1 depicts some popular applications of PLC. Going beyond the simple enjoyment of Internet use or PLC-based LAN networks, other applications have emerged such as voice, video and multimedia communications, promoted by major alliances namely HomePlug (Homeplug Powerline Alliance, http://www.homeplug.org/) and HD-PLC (HD-PLC Alliance, http://www.hd-plc.org). On the other hand, smart grid and smart citiy services can naturally benefit from the fact that the existing wired electrical infrastructures are already available (Anatory et al., 2013; Galli et al., 2011). In the same line, smart grid applications can provide communication between plug-in electric vehicles (PEV) and their charging station, as well as communications between smart appliances such as heaters, air conditioners, washers, and other appliances (Lampe, 2016; Sharma and Saini, 2017). Other novel applications of PLC include automated metre reading (AMR) (Galli et al., 2011) and wireless power transfer system (Barmada et al., 2017).

Figure 1 Examples of major PLC applications (see online version for colours)



To stimulate worldwide PLC deployments, IEEE communication society and International Telecommunication Union-Telecommunication (ITU-T) are the major standards organisations that promote next generation home networking services using electrical networks, notably by developing standards such as IEEE 1901 (IEEE Standards Association, 2010; LeClare et al., 2017) and ITU-T G.hn standards (Rahman et al., 2011; G.9960, 2017). In fact, Europe, USA, and Japan are the most active markets regarding standardisation and regulation activities. In Europe, the most relevant such standard is the European Telecommunications Standards Institute (ETSI) and European Norm (EN) 50065 (Lampe, 2016). In the USA, PLC emissions are regulated through the Code of Federal Regulations, Title 47, Part 15 (47 CFR Chapter 15) by the USA Federal Communications Commission (FCC) [Berger et al., (2014), Chapter 11, Part III and Part IV]. However, the transmit power limits imposed by standardisation bodies and their interference risks, for instance, with other services such as amateur radio and military services, may decrease their performance in terms of data rates. Bearing in mind that the electrical supply networks were not natively designed for communication delivery, consequently, the low voltage/medium voltage supply networks used as transmission mediums for PLC access systems may act as an antenna producing electromagnetic radiation (FCC, 2017). Therefore, PLC systems have to ensure very low values regarding the electromagnetic emission and, accordingly, operate with limited signal power levels. As a result, this may impact the distances that can be covered, and the transmitted power level as well as the data rates that can be realised by PLC systems, can also be limited.

Moreover, multimedia content delivery on PLC infrastructures undergoes severe impairments due to additive power line noises, signal attenuation and multipath propagation accompanied by frequency-selective fading. More precisely, the asynchronous impulsive noise type caused principally by the high number of branches, power supplies, and switching transients in the PLC network (Zimmermann and Dostert, 2002). It is a damaging type of noise with hight power spectral density (PSD) of 50 decibels (dB) above the background noise level, short durations (microseconds and milliseconds), and random occurrences in bursts, usually block-structured for frequencies ranging from some hundred of KHz to 20 MHz, so that it can generate bit or burst errors in broadband (BB) communications over PLC (Zimmermann and Dostert, 2002; Degardin et al., 2002; Fertonani and Colavolpe, 2009). On the other hand, PLC standards exploit orthogonal frequency devision multeplexing (OFDM) technique which mainly splits a high data rate stream into a number of multiple low data rate streams, transmitted at different sub-channels to the receiver (Ma et al., 2005). Consequently, OFDM may be withstand to such harsh kind of noise by splitting its effect among numerous sub-carriers during the FFT operation at the receiver (Abdelkefi et al., 2005). However, when impulsive noise exceeds certain threshold, couple of impulses or one single impulse occurring during the transmitted OFDM signal may eventually affect received OFDM sub-carriers (in frequency domain) leading to dramatic performance degradations (Meng et al., 2005). Recent study at the University of Mauritius (Rajkumarsingh and Sokappadu, 2016) has shown that the noise with the highest impact on data transmission is impulsive noise and the narrowband (NB) noise has the least effect. Therefore, PLC signal protection techniques are vital in order to improve performance of PLC systems.

The contributions of this paper are summarised as follows:

- Firstly, we provide a comprehensive overview related to impulsive noise reduction techniques, including error handling mechanisms, modulations schemes, and detection and removal-based strategies [e.g., time-domain processing, iterative threshold-based, compressive sensing (CS), and sparse Bayesian learning (SBL)] (Section 4).
- Secondly, by exploring the literature review, comparison and the common weaknesses points of the existing impulsive noise error-resilient techniques, are outlined [Section 5 (Section 6)].
- Thirdly, future research directions to move forward in numerous strategies, notably error handling mechanisms, and signal processing-based strategies, are suggested (Section 7).

The rest of the paper is organised as follows. Section 2 presents the related work. In Section 3, we bring an overview on PLC systems, including ECM issues, NB and BB PLC standards. Section 4 presents noise types and impulsive noise modelling approaches. In Section 5, we bring an overview on impulsive noise reduction strategies. Comparison and common weaknesses points of these techniques are provided in Section 6. The challenges and future research directions are given in Section 7. Finally, Section 8 concludes the survey.

Table 1 Summary of related surveys on PLC systems

Authors	*Summary*
Pavlidou et al. (2003)	This article constitutes an overview of the research, application, and regulatory activities on PLC. Transmission issues on the power line are investigated and modelling approaches are presented. Besides, contemporary communication techniques and MAC issues are described.
Gungor and Lambert (2006)	The motivation of this paper is to provide a better understanding of the hybrid network architecture that can provide heterogeneous electric system automation application requirements. Communication technologies such as internet-based virtual private networks, PLC, and satellite communications and wireless communication, are described in detail.
Laguna and Barron (2008)	In this survey, the authors present recent development and open research issues on indoor PLC channel modelling, and in particular, on its transfer function. Then, the most representative indoor PLC modelling approaches are highlighted.
Ferreira et al. (2010)	This article discusses the hostile low-voltage network (i.e., the so-called distribution line communications (DLC) systems) as a transmission medium for PLC systems.
Sharma et al. (2011)	This paper presents a survey of PLC. PLC technology and bandwidth, multiple access schemes, channel modelling , are described therein.
Fang et al. (2012)	The authors survey the literature till 2011 on the enabling technologies for the Smart Grid. The role of PLC in the smart grid is briefly highlighted.
Peter (2014)	This paper presents a review of the techniques for the reduction of impulsive noise in PLC which is classified into four categories, namely time domain, time/frequency domain, error correction code and other techniques.
Cano et al. (2016)	This paper presents state-of-the-art in PLC from the applications to the medium. An overview of both NB and BB systems, covering potential applications, regulatory and standardisation efforts and recent research advancements in channel characterisation, physical layer performance, medium access and higher layer specifications and evaluations, are provided.

2 Related work

In Pavlidou et al. (2003), this article constitutes an overview of the research, application, and regulatory activities on PLC. Transmission issues on the power line are investigated and modelling approaches are presented. Besides, contemporary communication techniques and MAC issues are described. In Gungor and Lambert (2006) provide a better understanding of the hybrid network architecture that can provide heterogeneous electric system automation application requirements. Communication technologies such as internet-based virtual private networks, PLC, and satellite communications and wireless communication, are described in detail. In Laguna and Barron (2008) present recent development and open research issues on indoor PLC channel modelling, and in particular, on its transfer function. Then, the most representative indoor PLC modelling approaches are highlighted. In the same line, Sharma et al. (2011) present a survey of PLC technology and bandwidth, multiple access schemes, and channel modelling. Recently, Peter (2014) present a review of impulsive noise reduction in PLC which is classified into four categories, namely time domain, time/frequency domain, and error correction code techniques. More recently, Cano et al. (2016) presents a state-of-the-art in PLC from the applications to the medium. An overview of both NB and BB systems, covering potential applications, regulatory and standardisation efforts and recent research advancements in channel characterisation, physical layer performance, medium access and higher layer specifications and evaluations, are provided. A brief summary of related survey articles is presented in Table 1.

Compared to previous survey articles (Pavlidou et al., 2003; Gungor and Lambert, 2006; Laguna and Barron, 2008; Ferreira et al., 2010; Sharma et al., 2011; Fang et al., 2012; Peter, 2014; Cano et al., 2016), this survey presents a comprehensive overview related to impulsive noise suppression techniques, with a major emphasis on identifying research gap deducted after reviewing the existing prior works on impulsive noise reduction strategies in OFDM-based PLC systems. To be more specific, this survey addresses the common weaknesses points of the existing impulsive noise error-resilient techniques, and exclusively discusses some challenges and future research directions by alleviating existing reduction noise strategies. Besides, this paper provides an overview on standardisations sectors that promote home networking services through power lines, as well as some PHY layer specifications of Legacy PLC standards. The different types of noise in PLC transmission, with a major emphasis on impulsive noise modelling approaches, are also provided.

3 An overview on PLC systems

PLC technology permits transmission of multimedia data (e.g., data, image and video) using the already-existing power line networks. It mainly exploits the power line supply networks as a transmission medium that generally consist of the three legacy network levels used as a transmission medium for the realisation of PLC networks. These are high voltage (110–380 kV), medium voltage (10–30 kV), and low voltage (110–400 V) Hrasnica et al. (2004), interconnected to one another by transformers designed in order to allow only low frequency (50 or 60 Hz) electric signals to proceed through power lines. In the following, we sketch an overview of the electromagnetic compatibility (EMC) issues and authorised frequency bands, and the recent standardisation and regulation activities applied to NB and BB PLC systems.

3.1 EMC issues in PLC

Basically, EMC means that the PLC systems have to operate in an environment without disturbing the functionality of the other systems existing in this environment (Hrasnica et al., 2004; Lampe, 2016; Berger et al., 2014). For PLC systems, the emission limit and their own immunity threshold are reported in Berger et al. (2014). Bearing in mind that the electrical supply networks were not natively designed for communication delivery, consequently, the LV/MV supply networks used as transmission mediums for PLC access systems may act as an antenna producing electromagnetic radiation (Hrasnica et al., 2004). Therefore, PLC systems have to ensure very low values regarding the electromagnetic emission and, accordingly, operate with limited signal power levels. As a result, PLC systems are subject to severe restrictions concerning the transmitted power level. This may impact the distances that can be covered, as well as the data rates that can be realised by PLC systems, are limited. Another important aspect of the deployment of PLC networks is their authorised frequency bands. As agreed upon by the ITU (International Telecommunication Union), the allocated frequency bands is from 30 kHz up to 100 MHz. Recently, a useful classification of PLC systems according to frequency bands has been introduced in Berger et al. (2014): it distinguishes between ultra-narrowband (UNB), NB and BB PLC systems, operating between about 30–3,000 Hz, 3–500 kHz and 1.8–100 MHz, respectively. Moreover, the levels of immunity and emission are regulated by EMC standards such as CENELEC EN 50561-1 in Europe and FCC part 15 in USA. These EMC standards specified some PSD masks and imposed several notches in which the PSD masks have an upper band at –55 dBm/Hz and lower bound –85 dBm/Hz for BB communications (below 30 MHz) in order to avoid interfering with other services such as amateur radio and military services for instance (FCC, 2017; IEEE Standards Association, 2010). In fact, advanced signal processing techniques are applied in PLC devices ensuring higher degree of protection for radio services, such as cognitive radio and power management or notching techniques. Thus, higher emission limits is guaranteed while maintaining more efficiently the usage of the frequency bands authorised for PLC systems (Lampe, 2016).

3.2 NB PLC systems

Europe, USA, and Japan are the most active markets regarding standardisation and regulation activities (Hrasnica et al., 2004). In Europe, for instance, the most relevant such standard is the ETSI and EN 50065 (Lampe, 2016). The latter, published first in 1991, was considered as a success story for NB-PLC covering the frequency range from 3 to 148.5 kHz. Besides, the EN distinguishes four frequency bands, which are commonly referred to as CENELEC-A (3–95 kHz), CENELEC-B (95–125 kHz), CENELEC-C (125–140 kHz), and CENELEC-D (140–148.5 kHz), respectively. In the USA, PLC emissions are regulated through the Code of Federal Regulations, Title 47, Part 15 (47 CFR chapter 15) by the US Federal Communications Commission (FCC). Moreover, major NB-PLC standards (LeClare et al., 2017; PRIME White Paper, 2017; Razazian et al., 2010) have implemented PHY layer specifications, based on OFDM systems that provide a transmission rate ranging between 10 kbps and around 500 kbps. For ianstance, PRIME alliance (PRIME White Paper, 2017) designed a NB-PLC standard, dedicated to smart grid services over the electrical networks, providing a transmission PHY rate up to 200 kbps in the frequency band of 3 kHz up to 95 kHz, based on OFDM technique with convolutional encoder (CE). Razazian et al. (2010) specification, aimed at the smart grid, promoted by various electricity, has been standardised as ITU G.9903 G3-PLC, and the standards ITU-T G.9902 G.hnem and IEEE 1901.2 PLC exploit it as a basis. IEEE 1901.2 standard (LeClare et al., 2017) was developed by IEEE P1901 working group and it provides NB communications (for low frequency <500 kHz) with high data rate below 500 kbps, based on PRIME and G3-PLC PHY layer specifications. The ITUT G.hnem (G.9960, 2017) standard, on the other hand, addresses next generation of NB home networking transceivers such as electric vehicle supply equipment and indoor energy management system. Table 2 highlights the a timeline development of NB-PLC specifications and standards, more details on NB-PLC standars can be found in Berger et al. (2014, Chapter 11) and in Cano et al. (2016).

Table 2 Timeline for the development of NB-PLC specifications and standards (see online version for colours)

February 2008	PRIME specification made public
May 2009	PRIME alliance established
August 2009	G3-PLC specification made public
January 2010	ITU G.hnem start of project
March 2010	IEEE 1901.2 authorisation of project
January 2011	IEEE 1901.2 first draft
September 2011	G3-PLC alliance established
December 2011	ITU-T G.9955 (PHY) ITU-T G.9956 (DLL) (G3-PLC and PRIME as annexes)
October 2012	ITU-T publishes G.9902 (G.hnem) G.9903 (G3-PLC) G.9904 (PRIME) supersede G.9955/56
December 2013	IEEE 1901.2 publication

3.3 BB PLC systems

Regarding BB-PLC systems, there have been many efforts to standardise indoor communications, notably by HomePlug power line alliance (Homeplug Powerline Alliance, http://www.homeplug.org/), HD-PLC alliance (HD-PLC Alliance, http://www.hd-plc.org), and IEEE P1901 working group (IEEE Standards Association, 2010). Table 3 highlights the a timeline development of BB-PLC specifications and standards. HomePlug alliance (Homeplug Powerline Alliance, http://www.homeplug.org/) was created in 2000 to stimulate communications over power lines, and until now has produced three major specifications HomePlug 1.0, HomePlug AV (audio-video), and HomePlug AV2. The first release of HomePlug alliance was HomePlug 1.0, in June 2001, with raw transmission PHY data rates up to 14 Mbps by using OFDM with temporal windowing (refereed as windowed-OFDM or DMT) technique in the frequency band 4.5 MHz to 21 MHz. On the one hand, the Homeplug AV markets, provide data rates up to 200 Mbps in the frequency bands from 2 to 28 MHz, based on OFDM with turbo convolutional encoding schemes. On the other hand, HomePlug AV2 standard provides additional features, such as MIMO with beamforming techniques, higher order mapping format, and power save modes to improve power efficiency of PLC modems. It provides an extended frequency bands from 30 up to 86 MHz and a data rates up to 2 Gpbs at its PHY layer specification, dedicated specifically for next-generation home networking services (e.g., voice over IP, HDTV, and 4 K Ultra HD video streams), fully coexist and interoperable with the previous HomePlug AV specifications. Another alliance that promote indoor PLC systems, namelly HD-PLC alliance (HD-PLC Alliance, http://www.hd-plc.org) was established in 2007, founded by Panasonic. It designed PLC modems based on Wavelet-OFDM transmission technique with

Reed-Solomon (RS) and convolutional encoding, providing maximum transmission rate of 190 Mbps in the frequency band 4-28 MHz. Panasonic's HD-PLC specification (as a fast Ethernet adaptor) enables easy set-up (easy setting and configuration where no PC required), high-speed communication (can support voice, gaming, and HD-TV over IP), and high reliability. Nowadays, the aftermentioned specifications (HomePlug AV and HD-PLC) have been involved in the IEEE 1901 standard (IEEE Standards Association, 2010), by the IEEE P1901 working group which has been approved and published since December 2010. Accordingly, IEEE 1901 specifies an inter-system protocol that allows coexistence between both BB-PLC technologies. Finally, the ITU-T G.hn standard (G.9960, 2017) was developed for next-generation home networking over power line. It make use scalable OFDM and block low-density parity-check code (LDPC), and allows transmission PHY rate up to 1 Gbps. More details on development of BB-PLC standards can be found in Berger et al. (2014, Part III and Part IV).

Table 3 Timeline for the development of BB-PLC specifications and standards (see online version for colours)

June 2001	HomePlug 1.0 released
June 2005	IEEE 1901 authorisation of project
August 2005	HomePlug AV released
April 2006	ITU G.hn atart of project
December 2008	Baseline of the IEEE standard confirmed
December 2008	ITU-T G.9960 consented
December 2010	IEEE 1901 publication
June 2010	ITU-T publishes G.9960 (PHY), G.9961 (DLL) G.9972 (coexistence)
June 2010	HomePlug Green PHY released
December 2011	ITU-T G.9963 published
January 2012	HomePlug AV2 released

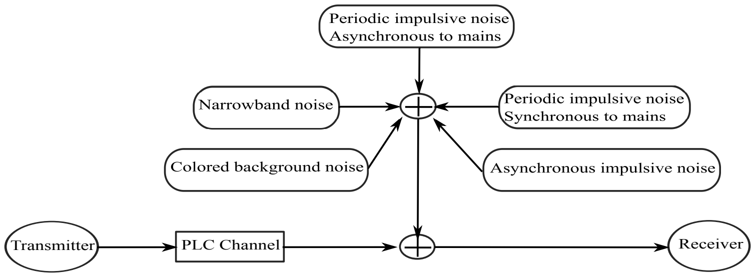
4 Noise in PLC: types, characteristics, and modellings

Beside the aberrant properties of the PLC channel, the noise types observed through PLC transmission (indoor or outdoor mediums) exhibit impulsive behaviors combined to background and NB noises. More specifically, the additive power line noises present over indoor PLC mediums are most often not Gaussian but impulsive. Recent study at the University of Mauritius (Rajkumarsingh and Sokappadu, 2016), has shown that the noise with the highest impact on data transmission is impulsive noise and the NB noise has the least effect.

4.1 SISO-PLC noise types and characteristics

There are five commonly known classification of noise types in PLC, as depicted in Figure 2, including coloured background noise, NB noise, periodic impulsive noise asynchronous or synchronous to the mains frequency (typically 50/60 Hz), and the asynchronous impulsive noise (Zimmermann and Dostert, 2002). As a matter of fact, three major classes can be distinguished, these are impulsive noise, NB noise, and background noise.

Figure 2 Noises classification in the PLC transmission

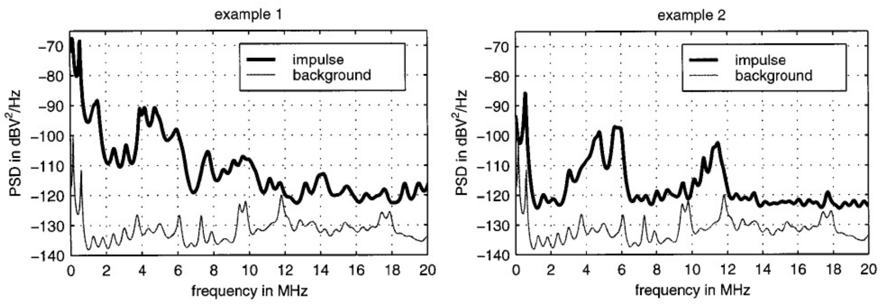


Source: Zimmermann and Dostert (2002)

Basically, the impulsive noise is generated by electronic devices connected to the indoor electrical grids, such as switched power supplies, switching of rectifier diodes, light dimmers or compact fluorescent lamps (Zimmermann and Dostert, 2002; Berger et al., 2014; Cortes et al., 2010). Due to the periodic nature of the mains frequency, switched power devices generate synchronous impulses with a repetition rate of 50 or 100 Hz (in Europe) to mains period or frequency. This type of noise is of short duration (some microseconds) and PSD decreasing with frequency. While, other power supplies generate periodic asynchronous impulses with higher repetition rate between 50 and 200 kHz to the mains frequency. Compared with the Gaussian noise, the PDF of impulsive noise has heavier tails along with large values that exceed a few standard deviations (Dai and So, 2018). These large values are considered as outliers under the conventional Gaussian noise model. On top of that, impuslive noise is assumed to occur in bursts and can corrupt blocks of received samples (Zimmermann and Dostert, 2002), which may be the mainly challenge for reliable multimedia data transmission in BB PLC systems (Lampe, 2011). Finally, switching transients within the indoor electrical network can generate asynchronous impulses of durations of some microseconds up to a few milliseconds with random occurrence and relatively higher PSD. Figure 3 depicts the mean PSDs of two impulse events (Zimmermann and Dostert, 2002), where both impulses exceed the PSD of the background noise for at least 10–15 dB in the frequency band 0–20 MHz, while in certain portions of the same frequency band, impulse 1 (Figure 3 example 1) exceeds the background noise for more than 50 dB and impulse 2 (Figure 3 example 2) up to 30 dB. On the other hand, NB noise is mostly caused by broadcast radio stations operating in the short-wave and the frequency-modulation (FM) bands (Zimmermann and Dostert, 2002). This type of noise is of longer duration and occurring periodically in time, amplitudes that change with day time, and mostly sinusoidal signals with modulated amplitudes. In Degardin et al. (2002), it is mentioned that this type of noise may reach power levels of

30 dB greater than the background noise at frequencies greater than 1 MHz. Finally, the remaining power supplies noise sources, presenting relatively lower PSD and remaining stationary over periods of seconds and minutes or sometimes even for hours, namely the background noise. This latter is generally coloured, i.e., its PSD is usually low which, however, significantly increases at lower frequencies below 500 kHz. Consequently, it can damage multimedia transmission for NB-PLC systems. As depicted in Figure 3, experimental results shown that the average PSD of background noise varies in the range between –140 and –100 dBV^2/Hz in the frequency band (0–20 MHz) (Seventh Framework Programme, 2008). Other measurements show that, the resulting PSDs in the frequency band (1–100 MHz), vary in the range between –90 and –155 dBm/Hz, and exponentially decreasing towards high frequencies (Esmailian et al., 2003).

Figure 3 PSD of the impulse events



Source: Zimmermann and Dostert (2002)

4.2 SISO-PLC noise modelling

In this subsection, we bring a highlight about background and impulsive noise modelling approaches. The background noise models have been usually derived through measurements campaigns. Regarding impulsive noise modelling approaches, they have been roughly categorised into two approaches: the deterministic and the statistical approaches. Deterministic models usually require to store measured impulsive noises, and remain relying on the PLC network topology (Meng et al., 2005; Tlich et al., 2009), while the statistical models randomly generate the impulsive noise, akin to some probability distributions derived from the measurements and commonly described by analytical formulas (Zimmermann and Dostert, 2002; Middleton, 1977; Vaseghi, 2008). In the following, we briefly sketch some of the relevant deterministic-based approaches and statistical-based approaches for both background and impulsive noises.

4.2.1 Background noise models

In literature, there are two methods for modelling the background noise. The first one is referred to the spectrum fitting method where the measured noise PSD is fitted into certain mathematical functions of frequency with reasonable number of parameters (Seventh Framework Programme, 2008; Esmailian et al., 2003; Guillet and Lamarque, 2010). In this case the noise is approximated by several sources of Gaussian noise in non-overlapping frequency bands with different noise powers derived from the measured PSD. The second method gives information on the random aspect of the noise at a particular frequency, it is referred to as statistical analysis method (Kim et al., 2008).

Esmailian et al. (2003) background noise model

Esmailian et al. (2003) have presented a straightforward three-parameter background noise model, where the noise is considered as Gaussian with a PSD given by

$$N_{nb}(f) = a + b|f|^c, \quad dBm/Hz \tag{1}$$

where parameters a, b and c are derived from measurements conducted in Canadian building and f is the frequency up to 30 MHz. The PSD of background noise exhibits a typical exponentially decreasing model (Seventh Framework Programme, 2008). Latter, in Guillet and Lamarque (2010) claimed that the Esmailian et al. noise model is not uniformly distributed in frequency since the background noise is coloured and more dominant in lower than in higher frequencies. Thus, the authors proposed a new PSD function that integrates the time dependence, as well as the mains frequency, as follows

$$N_{nb}(f) = a + \frac{b}{sqrt(f)}, \quad dBm/Hz \tag{2}$$

where the parameter b is redefined as $b = \beta_1|sin(2\pi 2ft)| + \beta 2$ where β_1 and β_2 represent a scale and a translation factors respectively. In this way, this new model can be seen has a unified model one which takes into account the standard PSD background noise model (1) and the periodicity of the background noise model.

OMEGA background noise model (Seventh Framework Programme, 2008)

The OMEGA's background noise model is based on measured PLC channels, it provides the typical character of the background noise in the frequency domain. The general mathematical form of the noise PSD is given by

$$N_{Omega}(f) = 10log10(\frac{1}{f^x} + 10y), \quad dBm/Hz \tag{3}$$

where parameters x and y are the quadratic decay and the noise floor, respectively.

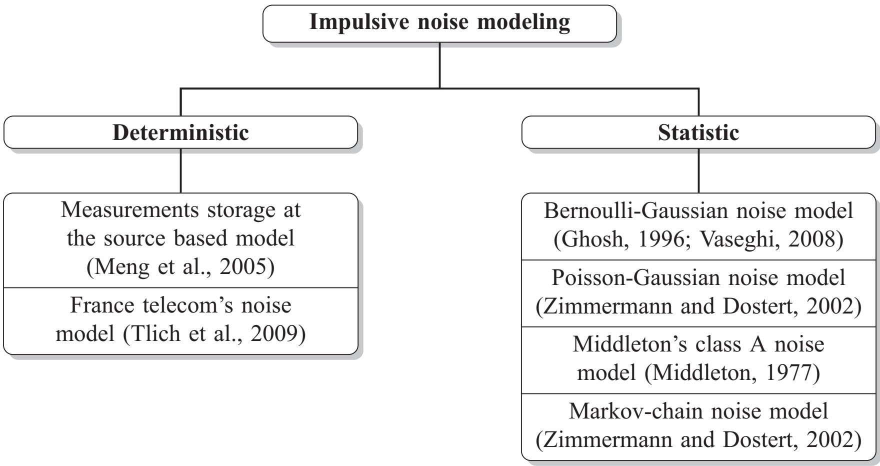
Other models for the background noise

A closed form mathematical model of the power line background noise has been proposed in Kim et al. (2008), based on the Nakagami-m distribution. However, the closed form may be further simplified to characterise the performance of the PLC receiver with satisfactory precision. In Andreadou and Pavlidou (2011), the background noise was considered to be formed of the coloured background noise and the NB noise, since they have similar effects. However, in Benyoucef (2003) proposed three model parameters which characterise the PSD of the noise in an accurate manner, as they were considered as random variables with space-dependent statistical distributions. The model is based on extensive long-term measurements in office and home environments, and the mathematical description of the model in described in Benyoucef (2003). Such PSD noise modelling is referred to as statistical analysis approach, where it can well describe the statistical characteristics of the PSD noise at a particular frequency.

4.2.2 Deterministic-based impulsive noise models

Figure 4 shows a representative deterministic-based impulsive noise models. There are two deterministic impulsive noise models, these are the measurements storage at the source-based model and the measurements storage at the France Telecom Orange Labs model.

Figure 4 Impulsive noise modelling approaches



Measurements storage at the source-based model

This model, also known as *ad hoc* model, has the advantage to efficiently reproduce practical impulsive noises at the source either in time or in frequency domain (Meng et al., 2005). Let's $S_j(f)$ denotes the stored impulsive noise PSD, generated by a given electrical appliance j. The resulting total PSD $S_t(f)$ of the impulsive noise seen by the receiver is therefore a summation of all noise PSDs corresponding to each noise source, considering that the electrical appliances are independent to each other. The $S_t(f)$ is therefore given by

$$S_t(f) = \sum_{j=1}^{n} S_j(f)|H_j(f)|^2, \tag{4}$$

where n is number of noise sources, and $H_j(f)$ represents the PLC channel transfer function between the noise source j and the receiver. However, the model remains dependent on the involved electrical appliances and can nevertheless lead to the storage of multiple impulses realisations, as the number of the appliances increases.

France Telecom Orange Labs model

France Telecom Orange Labs have proposed a promising impulsive noise modelling approach (Tlich et al., 2009), based on measurements storage at the source, providing a noise classification according to the 'in-devices' or appliances (e.g., electrical switches, thermostats, electrical plugs, laptop, and electrical engines) that are actually responsible of impulsive noise occurrence in electrical in-home networks. As a matter of fact, it is shown that the structure of impulsive noise does not depend on the electrical device itself; however, it depends on the in-devices or appliances components. After that, six different classes of impulsive noise were proposed, and a random generator of impulsive noise is proposed for each class, generated by 23 different domestic appliances. Besides, for each class, three representative impulsive noises were associated, representing the median, short and long impulse durations. Nevertheless, this model remain very dependent upon the electrical network configuration and to the 'in-devices' that may be present in domestic appliances. It is therefore interesting to investigate statistically-based approaches for impulsive noise modelling at the receiver side.

4.2.3 Statistical-based impulsive noise models

BG model

The Bernoulli-Gaussian (BG) noise model is often used to model impulsive noise in OFDM systems (Ghosh, 1996; Vaseghi, 2008; Zhidkov, 2008; Caire et al., 2008). From Ghosh (1996), it can be modelled as the product of a real Bernoulli process and a Gaussian process as follows:

$$u_m = b_m w_m, \quad m = 0, 1, 2, ..., N-1 \tag{5}$$

where w_m is a complex white Gaussian noise with zero mean and variance σ_u^2 and b_m is the Bernoulli-process with probability $P(b_m = 1) = p$. The sequence of BG noise model u_m are i.i.d random variable with the probability density function (PDF):

$$P(\nu_m) = (1-p)G(\nu_m, 0, \sigma_w^2) + pG(\nu_m, 0, \sigma_w^2 + \sigma_u^2) \tag{6}$$

where $G(.)$ is the Gaussian pdf, $\nu_m = u_m + w_m$ is the total noise seen by the receiver, σ_w^2 and σ_u^2 are the AWGN variance and the impulsive noise variance, respectively.

PG model

The Poisson Gaussian (PG) noise model is a promising noise model since it describes well the characteristic of impulsive noise (Zimmermann and Dostert, 2002; Vaseghi, 2008; Al-Mawali et al., 2009, 2008). Basically, the impulsive noise occurs according to a Poisson distribution with a rate λ units per second, hence the probability of an event of k arrivals in a time interval of T:

$$P(k, T) = \exp(-\lambda T)\frac{(\lambda T)^k}{k!}, \quad k = 0, 1, 2, \tag{7}$$

where (λT) represents the average number of impulses that occur in a time interval of T. According to Vaseghi (2008), the PDF of impulsive noise u_m in a time a time interval Δt is given by:

$$P(u_m) = (1 - \lambda\Delta t)\underbrace{\delta(u_m)}_{Diracpdf} + \lambda\Delta t \underbrace{G(u_m)}_{Gaussianpdf} \tag{8}$$

where $\delta(u_m)$ is Dirac PDF that models the absence of impulses, and $G(u_m)$ represents the Gaussian pdf that models the amplitude of impulses.

Middleton class A model

Another widely used noise model to represent impulsive noise on PLC channels is Middleton's Class A (MCA) noise model (Middleton, 1977; Vaseghi, 2008; Zhidkov, 2008; Ahadiat et al., 2017; Lin et al., 2013). Basically, the MCA model is a statistical-physical model of man-made electromagnetic interference, and it consists of white Gaussian background and non-Gaussian impulsive noise. According to Middleton (1977), the instantaneous impulsive noise amplitudes are i.i.d random, given by the PDF formula:

$$p(u) = e^{-A} \sum_{m=0}^{\infty} \frac{A^m}{m!} . \frac{1}{\sqrt{2\pi\sigma_m^2}} \exp\left(-\frac{u^2}{2\sigma_m^2}\right) \tag{9}$$

where $\sigma_m^2 = (\sigma_g^2 + \sigma_u^2) . \frac{\frac{m}{A} + \Omega_{GIR}}{1+\Omega_{GIR}}$ is the total noise power, $A \in [10^{-2}, 1]$ is the impulsive index and represents the average number of impulses per unit time, σ_g^2 is the Gaussian noise variance, σ_u^2 is the impulsive noise variance, and $\Omega_{GIR} = \frac{\sigma_g^2}{\sigma_u^2} \in [10^{-6}, 1]$ is the mean power Gaussian-to-impulsive noise ratio.

Partitioned Markov-chain model

A typically statistical model, partitioned Markov-chain, can be used to describe the occurrence of asynchronous impulsive noise events that can generate the bit or burst errors in PLC (Zimmermann and Dostert, 2002). By that, the partitioned Markov chain may contain a variable number n states $z_{i=1,\dots,n}$, and an output function $\Xi(k)$ at time instant k described by:

$$\Xi(k) = \Xi(z(k) = z_i) \begin{cases} 0, i \in \alpha \\ 1, i \in \beta \end{cases} \tag{10}$$

where $\alpha_{i=1,\dots,v}$ represents the states where no impulse event occurs and $\beta_{i=v+1,v+2,\dots,n}$ represents the occurrence of an impulse event. From Markov chain viewpoint, transitions states are introduced to summarise the transitions from set α to set β and *vice versa*, by considering two independent transition probability for the impulse free states (when impulsive noise is absent) and for the states where impulsive noise event occurs. Besides, another typical form of the Markov-chain, a so-called hidden Markov model can be used to emulate bursty structure of impulsive noise (Vaseghi, 2008; Korki et al., 2015). In Ndo et al. (2013) have proposed a novel bursty impulsive noise model based on hidden Markov model, whose realisations follow a MCA distribution.

4.3 MIMO-PLC noise characterisation

It is a well-known fact that multiple-input multiple-output (MIMO) communications are popular in the wireless and radio-mobile domains where they mainly exploit the spatial diversity to improve coverage, or rather, to improve data rate with respect to legacy SISO schemes by deploying multiple transmitter and receiver antennas. In the last 20 years, the interest of the PLC community on MIMO-PLC noise characterisation and modelling has been heavily investigated (Veronesi et al., 2011; Schneider et al., 2012).

Figure 5 SISO-PLC channel (see online version for colours)

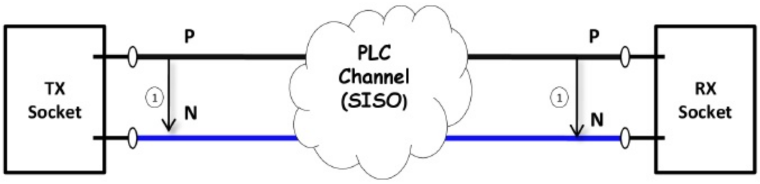
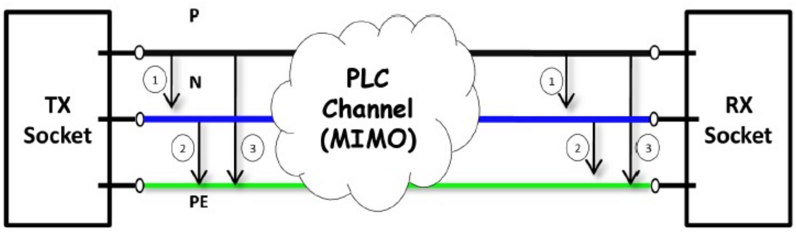


Figure 6 MIMO-PLC channel (see online version for colours)



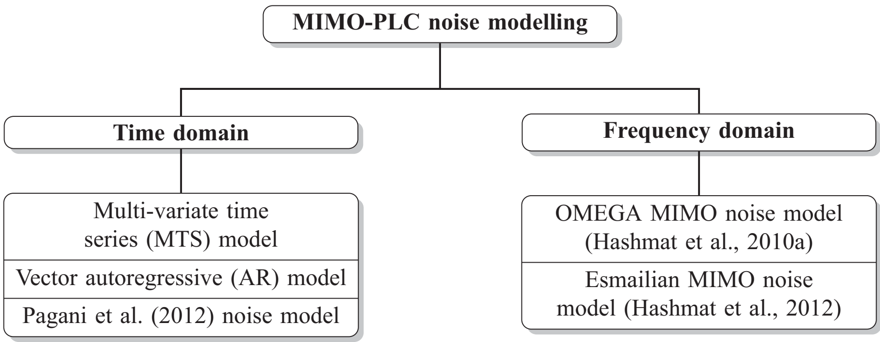
Several countries have conducted excessive measurements in order to provide MIMO-PLC noise correlation and its effect on the channel capacity (Schneider et al., 2012). Note that, the PLC channel has long been regarded as a SISO channel based on two conductors between two outlets (sockets). This is known as the differential-mode channel between the phase (P) and neutral (N) wires, as depicted in Figure 5. Similarly, in the PLC context, MIMO transmission can be deployed by exploiting the presence of multiple conductors, i.e., the three-wire in-building electrical installations. Basically, MIMO-PLC systems are supposed to exploit a three-conductors channel for data transmission between two outlets, these are P wire, N wire, and protective earth (PE) (Hashmat et al., 2010b). Figure 6 depicts the MIMO-PLC channel for three-wire installations with differential signal feeding through the wires. However, according to Kirchoff's rule, i.e., the sum of the three transmitted signals must be equal to zero. Thus, at the transmitting antennas, only two out of the three possibilities can be used independently. Accordingly, the third feeding option can be exploited and thus contribute to additional coverage and data rate. For instance, in a 2×3 MIMO feeding option, the average capacity gain ranged between 1.8 and 2.2 can be achieved depending on the transmitter's power level [Berger et al., (2014), Part II]. On the other hand, in Berger et al. (2014, Chapter 5), experimental results of the MIMO-PLC noise that were conducted in 31 different dwelling units in five European countries, including Belgium, France, Germany, Spain and the UK, are presented. The results have shown that strongest correlations were measured between the three receiving ports. Consequently, MIMO-PLC noise correlation helps to increase the MIMO channel capacity. On the other hand, the level of the measured noise PSD (in the band 0–100 MHz) revealed that is comparable in Germany, France and the UK, except for frequencies above 70 MHz, where France presents larger values. The highest noise recorded below 10 MHz and above 90 MHz was observed in Spain, however, in the frequency range (40–80 MHz), the median of the noise PSD found for this country are among the lowest ones. Furthermore, the characteristics of the measured noise were analysed in the time domain, and four typical structures were identified, these are stationary noise, periodical 50 Hz synchronous and asynchronous noise structure, and strong impulsive structure. A more promising analysis of

MIMO-PLC noise characteristics, was reported in Pagani et al. (2012), based on a European field measurement in the framework of the ETSI STF410, which can will serve as a basis for the definition of a statistical model of MIMO-PLC noise in Europe.

4.4 MIMO-PLC noise modelling

Figure 7 shows a representative MIMO-PLC noise modelling approaches, through both time domain and frequency domain modelling techniques.

Figure 7 Representative MIMO-PLC noise modelling



Source: Hashmat (2012, Chapter 4)

4.4.1 Time-domain models

In a time-domain MIMO model capturing the correlation between the received noises at different one of the most important features one wishes to capture is the correlation between the signals received at the three receiving ports. There are two time-domain MIMO noise modelling approaches, these are multivariate time series (MTS) model and vector autoregressive (VAR) model [see Berger et al., (2014), Part I Chapter 5]. Basically, MTS is a powerful model that was used for modelling and forecasting of the future values of time sequences, usually based on the VAR mathematical framework. This model was demonstrated in the context of MIMO-PLC noise where it was applied to a small series of noise measurements conducted in French houses. A $VAR(p)$ model of order p for an MTS with m variables takes the following mathematical form:

$$x_t = w + \sum_{l=1}^{p} A_l X_{t-l} + \epsilon_t, \quad cov(\epsilon_t) = C \tag{11}$$

where x_t are the vectors representing the MTS at a given time instant t, w serves to introduce the mean value if the MTS has non-zero mean, $A_l, ..., A_p$ are the model coefficient matrices, ϵ_t are zero-mean uncorrelated random noise vectors, and C is the noise covariance matrix. In Hashmat (2012, Chapter 4 Section 4), the results show that the $VAR(15)$ model successfully regenerates the spectral characteristics of the measured MIMO-PLC noise at a given socket.

4.4.2 Frequency-domain models

A detailed frequency domain analysis of the MIMO-PLC noise has been proposed in Hashmat et al. (2010b, 2012). These models are based on two existing SISO noise models (Subsection 4.2.1): the omega model (Seventh Framework Programme, 2008) and the Esmailian model (Esmailian et al., 2003). Similar to SISO-PLC background noise analysis, measurements revealed that the noise has a frequency dependent nature, and the noise level is higher at the lower frequencies while the level decreases as the frequency increases, including all three receiving ports. Moreover, lower correlation between P-N and P-PE noises were observed, and the same is true for P-N and N-PE noises also, derived from the cross correlation function between noise sequences of the MIMO-PLC channel. On the other hand, the results in Hashmat (2012, Chapter 4 Section 3) show that both models offer similar root mean square error statistics, though OMEGA-based model has a slight edge over the Esmailian-based model. However, the OMEGA model is simpler since it has only two parameters compared to three parameters of the Esmailian model.

5 Impulsive noise reduction

When considered as a transmission medium for communications signals, along with the increasing on-demand for more reliable multimedia transmission, PLC technology – either SISO or MIMO ones – are subject to various challenges such as high frequency selectivity, attenuation, and multiple additive noises. This section discusses various approaches to deal with the impulsive structures that occur on PLC channels, or so-called impulsive noise. Note that, impulsive noise reduction are considered in billion works, thus we can only give a brief overview on conventional and recent contributions in the field without any claim of completeness. In the following, we first bring impulsive noise reduction methods based on error handling strategies, then approaches based on forward error correction (FEC) and interleaving are presented, after that modulation schemes for impulsive noise mitigation are mentioned, and finally signal processing-based strategies are deeply presented.

5.1 Error handling mechanisms

5.1.1 ARQ-based strategies

Basically, automatic repeat request (ARQ) strategies consist in setting a communication procedure between the transmitter and the receiver, where the receiver requests the retransmission of a data unit that has not been correctly received, usually requests in a form of positive acknowledgement (ACK), negative ACK or wait for the transmitter to time out (Hrasnica et al., 2004). Furthermore, the legacy ARQ mechanisms are three types of procedure: send-and-wait, go-back-N, and selective reject, and they are specified in PLC draft standards and specifications such as PRIME (PRIME White Paper, 2017), HomePlugAV (Homeplug Powerline Alliance, http://www.homeplug.org/) and IEEE 1901 (IEEE Standards Association, 2010), standards. Note that, when an impulsive noise disturbance occurs, a number of data segments can be affected, hence erroneous segments are retransmitted by ARQ mechanisms. Consequently, only a smaller portion of the PLC network capacity is used for the retransmission, which improves the network utilisation (Hrasnica et al., 2004). Besides, network utilisation can be further increased by the application of ARQ-plus mechanisms. On the other hand, ARQ retransmission strategy may induce time delays and inherent spectral efficiency loss that may be exorbitant for real-time services such as video-streaming over PLC. For this reason, alternative solution such as hybrid ARQ strategies (Chen et al., 2013), that are combinations of ARQ and FEC solutions, can also be suitable to be applied in PLC systems.

5.1.2 FEC-based strategies

FEC-based strategies, also referred to as channel coding techniques, are widely used solutions by several PLC standards to achieve reliable transmission over noisy channels. PRIME specification (PRIME White Paper, 2017), for instance, popularly used in automatic metering for NB-PLC, has employed a basic CE with bit interleaving to combat NB interferences. G3-PLC (Razazian et al., 2010) for smart grid employed both CE and RS coding in order to mitigate errors caused by background noise and impulsive noise. As for BB-PLC, the IEEE P1901 (FFT-based) (IEEE Standards Association, 2010) standard used the turbo CE for channel coding, and the IEEE P1901 (wavelet-based) used concatenated RS and CE coding while LDPC codes can optionally be used instead.

In Ferreira and Vinck (2000), Ferreira et al. (2005) and Swart et al. (2007), the benefits of combining permutation codes with convolutional codes to form permutation trellis codes are discussed. The combination of M-ary frequency shift keying and permutation codes has special properties and error correcting capabilities that are suitable for disturbances in PLC. However, is not as robust for correcting burst errors with duration of several codewords. Furthermore, when the distance-preserving mappings (DPMs) are used, the advantages of permutation codes when combined with modulation M-FSK are retained, while making decoding easier by using the well known Viterbi algorithm. In Cheng and Ferreira (2012) further presented a method based on permutation decoding algorithm and a majority-logic decoding process. Due to its simplicity and low encoding/decoding complexities, the authors claimed that this scheme therefore can be suitable for a simple but robust NB-PLC system of practical interest.

Moreover, a combination of OFDM modulation with fountain and permutation coding is suggested in Cheng et al. (2013). The permutation encoding and decoding is the same as in Cheng and Ferreira (2012), additionally a fountain code is introduced to cope with disturbances of bursts of errors. Note that, fountain codes for impulsive noise correction in low-voltage indoor PLC were firstly presented in Amirshahi et al. (2006), where an OFDM system was used with a limited length interleaver, while fountain codes were used as an outer code with a combination of a convolutional code which was used as an inner code. There simulation results revealed that the concatenated scheme can be an excellent coding candidate for reliable BB communications in OFDM-based PLC systems. In Luby et al. (2007), the authors investigated Raptor codes (a class of fountain codes) for use in high-quality video distribution over PLC. It was observed that applying raptor codes on top of IP packets, quasi error-free performance can be achieved with only moderate bandwidth overhead and low complexity.

Carrying on with turbo codes, Tseng et al. (2013) proposed a turbo coded/decoded single-carrier system that can operate in impulse noise channels, exploiting the statistical knowledge of the impulse noise. More specifically, the authors proposed a clipping operation to be implemented in the trellis structure, therefore each received symbol can be considered as a modulated symbol affected by an additive memoryless clipping noise, of which the PDF can easily be obtained easily even in the absence of impulse statistics. In consequence, the turbo decoder metric can be adapted to blunt the impulse by capitalising on that PDF. Kim et al. (2010) analysed the performance of double binary turbo coding over the PLC channel in order to provide a significant gain in OFDM-based PLC systems, whereas the authors in Umehara et al. (2004) proposed optimum turbo decoding for turbo codes over PLC channels. However, the main drawback of turbo coding and decoding is the fact that the number of iterations used in the decoding process is relatively high which may increase the time processing. A much lower complexity FEC-based strategy have been proposed in Jin et al. (2015) and Hadi et al. (2016), where the authors investigated the performance and robustness of polar codes for different codeword lengths and noise scenarios in single-carrier and OFDM-based PLC systems. The result outcomes in Hadi et al. (2016) revealed that polar codes are efficient in error correction as they achieved a significant code gain compared to LDPC codes while maintaining remarkably lower complexity. However, polar codes are code lengths dependent, i.e., lower code length may affect the performance of OFDM systems.

LDPC coding and decoding for impulsive noise correction was considered in Pighi et al. (2009), Ardakani et al. (2005) and Oh et al. (2006). Most recently, Majumder and Verma (2016) proposed FEC-based multiple descriptions using LDPC-RS product codes for progressive transmission of an image over different fading channels for OFDM system. Zhang et al. (2016) have used uneven LDPC codes to make the image transmission much error resistive against AWGN channel considering case study of unequal error protection issues. Another study was conducted in Soliman et al. (2014), also used LDPC-based OFDM systems, but the technique uses chaotic Baker map with a target of minimising PAPR while improving the error resilient ability and also enhancing the efficiency of image transmission over fading channels. In Prasad et al. (2014) asserted that the performance of LDPC codes can approximate that of the turbo codes with higher block lengths, on typical and realistic PLC channels characteristics. Besides, the authors show that additional complexity associated with the increase in block length can be alleviated by the use of quasi-cyclic LDPC (QC-LDPC) codes. The latter exhibits error rates that approach the rates of the Turbo codes (at low SNRs) and outperform them at higher SNRs. Additionally, QC-LDPC codes (Andreadou and Pavlidou, 2010) also reduce the memory requirement significantly since the codes are generated using circulant permutation of a base matrix. Finally, the implementation of QC-LDPC has a straightforward structure and is easily implementable.

5.1.3 Interleaving techniques

When suddenly impulsive noise occurs, it induces burst errors, hence several blocks of received symbols are corrupted (Lampe, 2011). As a matter of fact, interleaving techniques are frequently exploited in many communication systems to prevent against burst errors. Examples for the application of interleaving technique in PLC systems are the IEEE 1901.2 and G3-PLC standards (LeClare et al., 2017; Razazian et al., 2010). FEC scheme such as convolutional codes may fail to deal with long impulse bursts, therefore, passing the coded binary sequences through an interleaving process increase their resiliency (Nguyen and Bui, 2008; Al-Mawali and Hussain, 2009). It was also claimed in Amirshahi et al. (2006) that interleaver depth is of importance and increasing this parameter to 1024 improves the overall performance, while increasing the interleaver depth did not bring further improvement in the system performance. In Liu et al. (2016b), an optimised time-frequency interleaving scheme is proposed, which employs the block size optimisation to improve the anti-time-domain impulsive noise capability in coded OFDM-based PLC system, where two criteria are proposed. Furthermore, the proposed interleaving scheme is at the symbol level (i.e., data symbol level) rather than the bit level, which leads to more effectiveness and low implementation complexity, compared to the legacy conventional block interleaving scheme. Unlike the conventional OFDM systems where the interleaving technique is implemented after the channel coding, the proposed works in Al-Dweik et al. (2010) aimed at performing the interleaving process post the IFFT, this allows spreading the corrupted samples over a large number of OFDM symbols, and thus after deinterleaving noise within each OFDM symbol becomes sparse in the time domain (Lin et al., 2013).

5.2 Modulations schemes for impulsive noise reduction

Communications over power lines undergo severe degradations mainly due to channel attenuation and multipath effect, as well as the presence of impulsive noise that can reach significant amount of level power so that it may erase a large amount of transmitted data. In order to deal with the frequency selectivity of the PLC channel, two major modulation schemes are frequently used: the single carrier (SC) modulations and the multi-carrier (MC) modulations. These modulations have already shown their robustness toward difficult environments and have been adopted in many standards such as digital audio/video broadcasting (DAB/DVB), digital subscriber line (DSL) technologies for OFDM, and various wireless communication standards applications [e.g., IEEE802.11a, IEEE802.16e (WiMAX), 3 GPP long-term evolution (LTE)].

5.2.1 SC modulations

The most commonly used SC digital modulation schemes are amplitude-shift keying (ASK), frequency-shift keying (FSK), pulse amplitude modulation (PAM), phase-shift keying (PSK), and quadrature-amplitude modulation (QAM), where the information (a binary sequence) is encoded in amplitude, phase or frequency of the carrier (IEEE Standards Association, 2010; PRIME White Paper, 2017; Razazian et al., 2010). Moreover, due to frequency-selective behaviour of PLC channels, SC modulation signals are seriously affected, so only poor performance can be usually achieved, especially for BB-PLC communications. On the other hand, low complexity modulation schemes, like PSK and M-aray QAM are the major modulation schemes employed in PLC standards. With respect to PLC, spread spectrum techniques (SST) systems can provide robustness against selective fading and NB interference. At the same time, SST usually achieve data rates up to some 2 Mbps with lower power spectrum. Thus, it is obviously that SST – although they are true BB techniques – are not necessarily high-speed techniques regarding data rates and spectral efficiency. Another easy handling technology called the direct sequencing spread spectrum (DSSS) was found to be well applied to wireless applications, can also be appropriate for PLC robustness against NB intererecnes. However, for both DSSS and SST systems, enhanced effort for synchronisation is necessary. Besides, if high spectral efficiency is the main goal, then BB OFDM technology can offer better results due to its high spectral efficiency, hence its use in major PLC standards. More results on practical applications of band-spreading technologies in PLC systems can be found in Lampe (2016, Chapter 5).

5.2.2 MC modulations

Basically, MC systems deploy a transmission technique where a high rate information signal is split out and transmitted through a large band channel at lower rate. Several MC schemes can be found in the literature, for instance: orthogonal frequency division multiplexing (OFDM), pulse-shaped OFDM, filtered multitone modulation (FMT), offset QAM-OFDM, discrete wavelet multitone (DWMT) modulation, and discrete cosine transform OFDM (DCT-OFDM). Some of them have been deployed in specifications of existing BB-PLC systems such as pulse-shaped OFDM (windowed OFDM) and DWMT (wavelet OFDM). Other MC schemes in the literature namely, vector-OFDM, concatenated OFDM-FMT, and cyclic block FMT which uses a cyclic filter bank instead of a linear filter bank, can have a relevance for PLC.

For instance, the advantage of discret wavelet transform (DWT) over FFT is that it is discrete both in time as well as scale, and in practice, DWT is implemented using filters (Koga et al., 2003). Such filters which have long impulse response, lower side-lobes over –35 decibels (dB) can be reached (Abad et al., 2005). Consequently, even if there are interferences from other systems, they would be only present in some sub-carriers which made it an appropriate scheme for PLC systems. Additionally, Wavelet-OFDM system does not require CP to be added to the OFDM symbol. In Mousavi et al. (2012), it is claimed that, the time and frequency localisation properties of the wavelet transform reduces NB and heavy impulsive noise which results in performance improvement. Besides, simulation results in terms of PAPR and BER revealed that DWT-OFDM is more robust against PLC channel effects compared to DFT-OFDM.

On the other hand, in Angulo et al. (2011) investigated the possibilities of layered division multiplexing (LDM), for its application in NB-PLC systems. Both theoretical calculations and simulation results based on PRIME specification in the CENELEC A-band, are provided. On the other hand, it has been claimed that non-orthogonal multiplexing (NOMA) technique (Ding et al., 2014, 2015) can be used to improve the throughput and spectral efficiency of wireless communication systems. Basically, NOMA technique aims at simultaneously transmit multiple data signals to different users with different power levels while each user, at the same time, occupies the entire available frequency band. More recently, the advantages of using NOMA compared to OFDM in PLC systems are described in Rabie et al. (2017). For instance, NOMA can also considerably reduce the severity of ECM issues associated with PLC, therefore, better coexistence with other wireless systems can be maintained.

5.2.3 SC vs. MC in impulsive noise environment

The BER performance comparison between QAM and OFDM modulations under impulsive noise have been thoroughly investigated in Ghosh (1996), Vaseghi (2008) and Ma et al. (2005), and closed-form expressions of the bit error probability were derived. It was particularly shown that OFDM, most of the time, outperforms the SC scheme (e.g., 64-QAM modulation), especially for moderate impulsive noise power (Ghosh, 1996). This can be explained straightforwardly. For a SC scheme (QAM or BPSK), when an impulse occurs, it affects at least one QAM/BPSK symbol while for OFDM, the impulse is spread (in frequency domain) over multiple sub-carriers (Ma et al., 2005). Therefore, a weaker or moderate impulsive noise scenario, is advantageous for OFDM as each sample suffers from a small amount of impulse power. In the opposite case, a whole OFDM symbol may be wiped out, leading thus to significant performance degradations compared to SC schemes (Ghosh, 1996). On the other hand, increasing the carrier number and the CP can also improve the BER performance of the OFDM system under the impulsive noise and multipath effects (Ma et al., 2005).

5.3 Detection and removal-based strategies

In this subsection signal processing based on detection and removal strategies at the receiver side to deal with impairments due to impulse noise, are presented.

5.3.1 Time-domain techniques

The time-domain techniques (Al-Mawali et al., 2009, 2008; Zhidkov, 2008; Ndo et al., 2010; Rabie and Alsusa, 2013, 2014) (commonly known as nonlinear preprocessor techniques), consist in clipping and blanking the high signal amplitudes of the received time-domain signal above a selected threshold value. Several studies have been presented in Ndo et al. (2010); Rabie and Alsusa (2013, 2014) in order to improve the performance of nonlinear preprocessor techniques. For instance, Ndo et al. (2010) have proposed a threshold optimisation based on false alarm and good detection trade-off of the clipping technique. Also, by combining impulse parameters estimation and threshold optimisation, they have also proposed an adaptive impulsive reduction scheme for highly and weakly disturbed impulsive noise scenarios. In Rabie and Alsusa (2013) and Rabie and Alsusa (2014) have introduced techniques to improve clipping/blanking using peak to average power ratio (PAPR) based on selective mapping scheme, and dynamic peak-based threshold estimation technique (Rabie and Alsusa, 2015). The authors have claimed that, minimising the PAPR may also minimise the probability of impulsive noise detection error, allowing improvement up to 3 dB in terms of SNR when compared to conventional nonlinear preprocessor techniques. However, the main challenge for these techniques is that the characteristics of impulsive noise must be apriori known (e.g., probability of occurrence) at the receiver. Therefore, inadequately selected thresholds may degrade BER performance.

In Himeur and Boukabou (2016a, 2016b) have proposed turbo coding and decoding combined with adaptive noise compensation based on the estimation of the impulse bursts using a novel blanking/clipping function to reduce burst errors and multipath effects in OFDM-based PLC. In Himeur and Boukabou (2017) have proposed a novel framework that consist of an adaptive noise clipping-based hybrid progressive median filter. The adaptive noise clipping algorithm is designed to dynamically estimate the noise threshold from the standard deviation of the noise and the peak value of the received noisy OFDM signal. However, their approach present some limitations that are: the parameters of the impulsive noise (i.e., standard deviation of the noise a probability of occurrence) are supposed to be known, that is to say, the performance can suffer when the noise model does not reflect the statistics of the impulsive noise or the parameters are inaccurate. Besides, suboptimal thresholds long with short-term changes in impulsive noise characteristics can degrade performance of PLC systems. Furthermore, as the magnitude of spikes in impulsive noise decreases, the performance of the receiver decreases.

In Soltanpu et al. (2017) have proposed a novel time-domain filter based on Masreliez's approximation in order to equalise the output of the PLC channel. The performance of the filter (nonlinear equaliser) is studied under (vector) VOFDM system over a multipath PLC in the presence of middleton class A impulsive noise model, and has proved to considerably improve BER successfully at low signal-to-noise ratios (SNRs). the authors have compared the Masreliez equaliser for different set of parameters of noise model with linear minimum mean square error (LMMSE) equaliser. As a matter of fact, the performance of the filter decreases when the impulsive noise and (VOFDM) signal become to close to each other; this means higher SNRs.

5.3.2 Iterative threshold-based algorithms

A more promising approaches have been proposed in Mengi and Vinck (2010), Hu et al. (2014), Ahadiat et al. (2017) and Laksir and Tamtaoui (2016), where the authors used iterative threshold-based algorithms to estimate impulsive noise in time-domain, then cancel it from the received signal either in time or frequency domains. In Mengi and Vinck (2010), the proposed iterative suppression algorithm reconstructs the OFDM signal in frequency domain and transforms it back to time-domain (by mean of IFFT) to start the next iteration. Next, the detected time-domain OFDM signal is subtracted from the original received signal, where the result is then processed by a threshold detector to estimate the complex amplitudes of the impulsive noise. Finally, the iterative process continues by subtracting the detected impulsive noise samples from the received signal until the maximum number of iterations is exceeded. However, the shortcoming of these techniques is that, the thresholds used to detect the impulsive noise relies on sample variance of the estimated noise terms. Recently, these techniques have been extended for impulsive noise reduction using MIMO-PLC systems (Hu et al., 2014; Ahadiat et al., 2017) and to mitigate the effects of impulsive noise on image transmission in OFDM-based PLC in Laksir and Tamtaoui (2016) and Laksir et al. (2017). More recently, the authors in Lopes et al. (2017) investigated iterative MMSE/MAP impulsive noise reduction techniques for OFDM systems. The proposed techniques are similar to previous works in Mengi and Vinck (2010), Ahadiat et al. (2017) and Laksir et al. (2017), however, when comparing with the work in Zhidkov (2003) proposed stronger theoretical foundation, and a new variance estimate. Additionally, the experimental results have shown that the proposed iterative techniques noticeably outperformed the legacy iterative techniques in Zhidkov (2003), at the expense of slightly increment of computation complexity and number of iterations.

Impulse response shortening filters, i.e., time-domain equalisers (TEQs), have been commonly used in reducing the interblock interference (IBI) by suppressing the tails of the composite impulse response (Celebi, 2003). However, Tan et al. (2012) claimed that the presence of impulsive noise in the channel may paralyse the operation of TEQs and subsequently lead to poor error performance. Thus, the authors proposed a multicarrier receiver that incorporates a constant false alarm rate algorithm and an iterative estimation technique (CFAR-IET) in conjunction with a TEQ. Besides, the buffering, sorting, removing and amplitude averaging (BSRA) processes, is presented. The results show that the BSRA-IET-TEQ scheme is an effective approach to reduce symbol error rate (SER) in impulsive channels while performing satisfactorily in Gaussian channels. In Khan and Shin (2017), FFT-OFDM-based and DWT-OFDM-based PLC systems are studied, and overlap frequency domain equalisation (OFDE) as a robust and efficient equalisation technique is presented. Moreover, linear precoding (LP) is also suggested for FFT and wavelet transform-based filter bank transceivers over the PLC channel. Results show that not only the proposed LP-based DWT-OFDM-OFDE transceiver performs better than the previous equalisation models, however, also the LP-based OFDM-OFDE at the expense of slight increment in computational complexity.

5.3.3 CS-based strategies

Impulsive noise estimation and removal based on CS techniques has gained a fast-growing research interest in the context of OFDM based PLC (Caire et al., 2008; Al-Naffouri et al., 2011; Mehboob et al., 2012; Al-Naffouri et al., 2014; Liu et al., 2016a). They mainly exploit sparsity, null and pilot tones, conenvex relaxation methods and simple least square (LS) or minimum mean-square error (MMSE), in order to estimate and remove the impulsive noise from the received time-domain signal. In Al-Naffouri et al. (2011), the proposed CS algorithm applies a coarse estimation of the noise's support and its refinement using a MAP metric, followed by MMSE estimation in order to minimise the errors of the estimated amplitudes. Furthermore, Al-Naffouri et al. (2014), have claimed that the proposed CS algorithms in Caire et al. (2008) and Al-Naffouri et al. (2011) make use of l_1 minimisation, which leads to a high computational cost and only exploits the sparsity information of the signal of interest. In Lampe (2011), author has proposed a promising approach to remove the impact of bursty impulsive noise by block-based CS, which is an extended of previous work in Caire et al. (2008) on CS-based convex relaxation methods. The proposed work in Lampe (2011), similar to the works in Caire et al. (2008) and Al-Naffouri et al. (2011), exploits null and pilot tones to estimate the amplitudes of bursty impulsive noise. Besides, sparsity information and bursty structure of impulsive noise are exploited to obtain nearly estimates of its realisations. Mehboob et al. (2012) have proposed multi mode CS scheme which adaptively changes the number of null and pilots according to the impulsive noise level. This aimed at improving better the cancellation of impulsive noise, when the impulsive noise sparsity changes significantly over time. Another more efficient CS approach has been proposed in Al-Naffouri et al. (2014). The CS framework exploits the sparsity and the a priori statistical informations (i.e., impulsive noise model and the free guard band sub-carriers in OFDM system), and a fast clustering algorithm; in order to obtain a nearly optimal impulsive noise estimation and removal at low complexity. Recently, Liu et al. (2016a), claimed that, by introducing the structured CS theory to impulsive noise recovery; the gap of research-lack on the reduction for MIMO-PLC systems is filled. They have proposed a structured a priori aided sparsity adaptive matching pursuit (SPA-SAMP) in order to reconstruct impulsive noise in accurate manner, which significantly improved the accuracy and robustness compared to that of the state-of-art methods. More specifically, the structured CS optimisation framework was formulated through the proposed spatially multiple measuring method, by fully exploiting the spatial correlation of the impulsive noise signals at different receive antennas.

Carrillo et al. (2010), Carriloo and Barner (2013), Sermwuthisarn et al. (2012) and Carrillo et al. (2016) have proposed other promising CS approaches for sparse signal and image recovery under impulsive noise. Carrillo et al. (2010) have proposed efficient CS frameworks to sample and reconstruct sparse signals in the presence of impulsive noise, based on Myriad projections and Lorentzian method. Besides, in Carriloo and Barner (2013) proposed another efficient iterative algorithm based on Lorentzian cost function to reconstruct sparse signals and images altered by impulsive noise. The algorithm exploits prior signal information in the recovery process and outperforms many sparse reconstruction algorithms. In addition, extensions of the Lorentzian iterative threshold algorithm to incorporate partial support into the recovery process, are also proposed.

Sermwuthisarn et al. (2012) have proposed impulsive noise rejection method for image reconstruction under noisy scenarios. The rejection method iteratively applies heuristic rule that is based on the energy distribution of the image data in wavelet domain to detect the existence of the impulsive noise before the reconstruction. The sparsity version of the image is obtained by utilising octave-tree discrete wavelet transform. Recently, the derived methods in Carrillo et al. (2016) outperformed some legacy CS techniques in impulsive environments, while achieving good performance in light-tailed environments, thus offering a robust framework for CS.

5.3.4 SBL-based strategies

Many other low complex approaches based on more sophisticated signal processing-based strategies have been proposed for impulsive noise estimation and mitigation, including SBL (Lin et al., 2013) and block iterative Bayesian algorithm (block-IBA) (Korki et al., 2015; Korki et al., 2016). For SBL approach in Lin et al. (2013) have proposed three SBL frameworks to estimate the impulsive noise. These are SBL framework using null tones and pilots, SBL framework using all sub-carriers, and SBL framework based on decision feedback which exploits the redundancy in the coded sub-carriers. The results show that, adapting the SBL algorithm to jointly estimate the transmitted sequence along with the sparse impulse noise vector from all subcarriers, provides up to 10 dB gain over a legacy OFDM receiver. Korki et al. (2015, 2016) have asserted that the impulsive noise in PLC satisfies non-i.i.d. property since it occurs in bursts with correlated samples. Hence, authors have proposed a novel block-IBA framework for block-sparse signals based on more realistic impulsive noise model. Besides, the block-SBL framework estimates the supports and amplitudes of the desired block-sparse signal iteratively based on expectation maximisation (EM) algorithm which is optimised with the steepest-ascent method. Accordingly, the proposed block-SBL efficiently reconstruct the block sparse impulsive noise when it contains a large number of blocks with short lengths, and and optimally selects the supports of the block-sparse impulsive noise by adaptive thresholding. Furthermore, the proposed Bayesian approach differs from Lin et al. (2013) as rather than employing SBL based on MAP and EM algorithms, they make use of a block iterative Bayesian algorithm that exploits the block sparsity of the impulsive noise for efficient noise estimation and removal. The authors have claimed that, the proposed (block-IBA) framework outperforms the CS-based approach in Caire et al. (2008) by more that 5 dB as well as the SBL framwork in Lin et al. (2013) to approximately 4 dB. On the other hand, conventional direction-of-arrival (DOA) estimation methods in (non-Gaussian) impulsive noise from the perspective of SBL view have been addressed in Dai and So (2018) to deal with different impulsive noise models, including Gaussian mixture model (GMM), generalised Gaussian distribution (GGD), compound Gaussian model (CGM), and α-stable distribution. Besides, to reduce the computational complexity of a Bayesoptimal algorithm, a fast alternating scheme is also proposed, compared to legacy EM approach in Lin et al. (2013). The authors claimed that the total computational requirement of the fast alternating algorithm (per iteration) is reduced at least by a factor of one order. Furthermore, an effective benchmarking study has been conducted, where the proposed algorithms are compared with the original SBL method, classical MUSIC, robust-MUSIC, and lp-MUSIC, as well as the Cramer-Rao bound (CRB) for DOA estimation.

6 Comparison of impulsive noise reduction strategies

Table 4 shows a qualitative comparison and summary of the different impulsive noise schemes with respect to PLC systems. Thorough this survey, when OFDM or MIMO-PLC systems are combined with FEC and interleaving, the numerical results are more impressive regarding BER performances; that is, when moderate or strong impulsive noise occurs. While dealing with bursty impulsive noise, CS and SBL approaches are even more impressive for low SNRs, since larger power levels make easier the detection and estimation of impulsive noise corrupted samples. On the other hand, time-domain processing techniques also provide better resiliency against impulsive noise, that is, also valid, when moderate or strong impulsive noise occurs. Additionally, by combining impulse parameters estimation and threshold optimisation, adaptive impulsive reduction scheme for highly and weakly disturbed impulsive noise scenarios, also provide noticeable improvements. As a matter of fact, the performance of such techniques decrease when the impulsive noise and (OFDM) signal become to close to each other, thus at higher SNR's the small magnitude of spikes in impulsive noise cannot be distinguish from the transmitted data. Consequently, BER performances diverge as the magnitude of impulses decrease, this is true at higher SNR.

Table 4 Qualitative comparison of different impulsive noise reduction schemes for PLC

	Error handling mechanisms	*Modulations schemes*	*Time-domain techniques*	*CS-based approaches*
Features	ARQ, FEC interleavers	SC, MC, FFT-OFDM, DWT-OFDM, MIMO	Clipping Blanking, iterative techniques	CS SBL frameworks
Modelling principle and basics	Retransmission Redundancy Interleaving Multiplexing	SC & MC transmission Orthogonality Cyclic prefix Equalisers Time-frequency diversity	Impulse detection Distribution of impulse noise Threshold-based Iterative Null and pilot tones	Sparsity prior (distribution) of signal information Convex relaxation methods Null and pilot tones MAP and EM
BER performance (high SNR)	Low	Low-medium	Low-medium	Low-medium
BER performance (low SNR)	Low-medium	Medium	Medium-high	Low-medium
Transmitter complexity	Medium	Low	Low	very low
Receiver complexity	Medium-high	Medium	Medium-high	Low-medium
Impulsive noise mitigation	Medium-high	Low-medium	Medium	Medium-high

Table 5 Scaling effectiveness of existing FEC-based impulsive noise reduction strategies

Authors	*Problem*	*Strategy*	*Strengths*	*Weaknesses*
Nguyen and Bui (2008)	Decoding performance of PLC systems disturbed by impulsive noise	Bit-interleaved coded OFDM with iterative decoding (BI-COFDM-ID)	Better BER performance	Larger decoding iterations No complexity discussion
Pighi et al. (2009)	Investigate communications systems impaired by impulsive noise	Trellis coded modulated and LDPC codes	Better BER performance Enhanced information rate	Computational complexity not computed
Cheng et al. (2013)	Mitigate the errors caused by impulse noise and narrow-band interference	Combination of OFDM modulation with fountain and permutation coding	Rateless erasure code Enhanced erasure probability	Less extensive analysis No effective benchmarking
Prasad et al. (2014)	Study the performance of LDPC and turbo codes in PLC	Comparative analysis of QC-LDPC performance	Enhanced BER performances Straightforward implementation	Block lengths dependency No complexity analysis
Hadi et al. (2016)	Investigated performance and robustness of polar codes in OFDM-based PLC systems	Enhanced decoding performance hard decision (HD) and soft decision (SD) decoding schemes	Better BER performance than LDPC Better performances using clipping and blanking techniques	Requires large codeword lengths
Liu et al. (2016)	Investigate new interleaving scheme to combat against the narrowband interferences and impulsive noise in PLC	Proposed optimised time-frequency interleaving scheme Employs the block size optimisation	Improved the anti-time-domain impulsive noise capability Shorter interleaving delay and less complexity	Increases latency for interactive applications Amount of impulsive noise reduction depends on the number (length) of interleavers $(K-1)$

Table 6 Scaling effectiveness of existing time-domain signal processing techniques

Authors	*Problem*	*Strategy*	*Strengths*	*Weaknesses*
Rabie and Alsusa (2013)	Investigate blanking clipping performances over PLC channel	PAPR reduction technique and selective mapping (SLM) scheme	Lower probability of impulsive noise detection Enhanced output SNR maximisation	Not suitable for real application No complexity discussion
Ndo et al. (2010)	General issue of impulsive noise reduction over coded PLC systems	Adaptive clipping technique False alarm probability	Better BER performance	No benchmarking and complexity discussion
Tan et al. (2012)	Investigate time-domain equaliser(TEQ) over impulsive noise channels	CFAR-IET in conjunction with a TEQ are proposed Novel BSRA processes are presented	Increased robustness against impulsive noise Reduced SER	Less effective benchmarking analysis No complexity analysis
Ahadiat et al. (2017)	Improve impulsive noise cancellation in MIMO-OFDM-based PLC	Proposed a novel adaptive threshold based on Neyman-Pearson criterion	Enhanced BER performance	Higher time-processing and computational costs
Himeur and Boukabou (2017)	Image transmission over OFDM-based PLC channel	Turbo codes combined with and median filter and median filter	Better BER-SNR performance	No complexity discussion
Soltanpu et al. (2017)	Investigate the performance of vector OFDM over PLC channels	Time-domain equaliser based on Masreliez approximation	Improved BER performance	Performance decreases for high SNRs values
Khan and Shin (2017)	Investigated performances of OFDM and wavelet OFDM PLC systems	Robust OFDE equalisation technique is presented	Effective comparative study with classical equalisation techniques	Slight increment in computational complexity

Table 7 Scaling effectiveness of existing CS and SBL-based impulsive noise reduction strategies

Authors	*Problem*	*Strategy*	*Strengths*	*Weaknesses*
Caire et al. (2008)	Impulsive noise reduction using CS for OFDM system	Exploit convex relaxation methods for impulsive noise removal	Competitive method to estimate the location of the impulses	Failure recovery when the number of impulses per OFDM block increases
Lampe (2011)	Impulsive noise reduction based on the application of block-based CS	Exploits burst structure of impulsive noise and null sub-carries to detect the location and its sample values	Better BER performances Efficient bursty impulsive noise reduction	Feasible for sparse impulsive noise signals No complexity analysis discussion
Liu et al. (2016a)	Impulsive noise reduction strategy for MIMO-OFDM PLC systems	Based on structured CS-based greedy algorithm Novel CS framework SPA-SAMP	Spatial correlation of impulsive noise samples Improved impulsive noise recovery	Large number of measurements are required
Lin et al. (2013)	Impulsive noise estimation and suppression using SBL	Exploits MAP and EM algorithms Proposed a lower complexity using sequential SBL	Improved BER performance Do not require prior knowledge of noise model parameters	Performance decreases when number of null and pilot tones decreases
Korki et al. (2015)	Novel bursty impulsive noise reduction method using Block-IBA	The method exploits the guard band null and data subcarriers	Better impulsive noise estimation Reduced computational cost	The framework depend on null tones Increased computation time
Dai and So (2018)	Investigate DOA estimation methods in impulsive noise	A Bayes-optimal algorithm is proposed New grid-refining procedures are introduced	Reduced the total computational requirement Effective comparative analysis	May be not feasible real-time applications

Next, let us look into the scaling effectiveness of major impulsive noise reduction strategies as shown in Tables 5, 6 and 7. However, we do believe that there are still many aspects and issues that need to be further studied in order to ensure the successful penetration of the impulsive noise reduction strategies in PLC systems. The common weaknesses points of the existing impulsive noise error-resilient techniques discussed in this section can be summarised as follows:

- *No focus on computational complexity:* the strategies of impulsive noise reduction are either based on powerful FEC schemes and time-domain techniques or a combination of them. It is drawn that, through the previous section, a few papers investigated the computational complexity of their proposed schemes.
- *No focus on hardware implementation:* all strategies are evaluated using Monte Carlo simulations or Matlab simulations and there is no interest on hardware implementation, which in our opinion, the most forgotten research-lack in these strategies.
- *Less original contributions:* majority of works towards impulsive noise reduction has either used existing FEC schemes (e.g., turbo codes and LDPC) or improved time-domain techniques (e.g., clipping/blanking and iterative algorithms), or a combination of them.
- *Less focus on benchmarking:* across the previous section there is either no benchmarking or ineffective comparative studies which make so tricky selecting robust strategies to cope with impulsive noise.
- *No focus on image and video transmission:* there is less attention on the impact of image and video transmission over OFDM-based PLC. Therefore, novel impulsive noise error-mitigation strategies should target multimedia transmission over PLC networks.
- *No focus on other transmission schemes:* majority of the presented works have used FFT-OFDM as the legacy PLC transmission scheme, while the proposed impulsive noise reduction strategies can also be investigated using other transmission strategies, for instance vector-OFDM (Soltanpu et al., 2017), OFDM-OQAM, and OFDM with index modulation (OFDM-IM) (Basar et al., 2017).

7 Challenges and future research directions of impulsive noise reduction in PLC

In this section, we highlight the main challenges and suggest future research recommendations to address them.

7.1 FEC-based strategies

The main drawback of FEC schemes is their high encoding/decoding complexity and overhead. Therefore, it is crucial to investigate suitable FEC scheme capable of achieving near error free transmission over additive PLC noises, more explicitly non-Gaussian impulsive noise. On the other hand, when dealing against PLC channels using interleaving techniques, random interleavers present generally better performance. However, they are not feasible for practical implementation. Consequently, the design and implementation of an interleaver suitable for PLC systems without memory conflict issues and lower delay are other challenging topic to be investigated. In future, for instance, to improve the error correction capabilities, interleavers (Liu et al., 2016b) can be combined with fountain codes (Cheng et al., 2013; Luby et al., 2007) to improve the performance of PLC networks. Additionally, foutain codes can also be combined with QC-LDPC (Prasad et al., 2014) in order to make the multimedia (e.g., image and video) transmission much error resistive against the severity of the impulsive noise and frequency-selectivity of PLC networks considering case study of unequal error protection issues (Zhang et al., 2016).

7.2 Modulation strategies

Modulation schemes, in great number and variety, have been developed and analysed in major PLC standards. Although early attempts have been made to explore the potential of non-orthogonal multiplexing schemes (NOMA) in PLC (Rabie et al., 2017). Other alternative digital modulation schemes have been already investigated, these are NOMA (Ding et al., 2014, 2015), spatial modulation (SM) (Basar et al., 2017), OFDM with index modulation [OFDM-IM (Basar et al., 2017)], and golden angle modulation (GAM) (Larsson, 2017). It is predicted that, based on recent studies, these novel schemes appear as innovative candidates for next generation wireless, optical, or wired networks; that is, due to the competitive advantages in terms of spectral and energy efficiency as well as hardware simplicity. Thus, in future, we strongly suggest the research community to investigate theoretical analysis, practical implementation issues, and demonstrate their possible applications in PLC.

7.3 Time-domain-based strategies

In Vaseghi (2008, Chapters 12 and 14), robust estimation of a parameter, such as the signal power, in the presence of impulsive noise, is considered. It was shown that the use of a two-sided predictor can result in further improvement in noise detectability as well as impulsive noise detectability can be improved by decorrelating the speech signal. On the other hand, another solution is to investigate special nonlinear filters such as the so-called nonlinear equaliser based on Masreliez approximation (Soltanpu et al., 2017) and the adaptive nonlinear filter based on a canonical piecewise linear (CPWL) approach (Zhai et al., 2016). Additionally, combination of Masreliez or CPWL filters with powerful decoding FEC schemes (e.g., LDPC and foutain codes) can be considered for coded PLC receivers, by simply feeding back the estimated data from an QC-LDPC decoder to the Masreliez filter, ensuring lower BERs, overhead control, end lower encoding and decoding complexity.

7.4 Iterative suppression algorithms strategies

We do believe that it will be interesting to investigate advanced theory of detection and estimation to ensure a good trade-off between improving the probability of a correct detection and reducing the false alarm probability (Van Trees, 2004). On the other hand, other iterative receiver for MIMO-OFDM systems based on sphere decoding has been shown to have lower average computational complexity (El Chall, 2015), while achieving a quasi-ML performance which give them advantages over legacy detection techniques such as MMSE detection and successive interference cancellation (SIC) detection. Optimisation of the computational complexity of the proposed iterative (receivers) suppression algorithms in hardware architecture can also be investigated in order to simultaneously perform the detection and the decoding processes in PLC receivers. Moreover, iterative joint detection, decoding, and channel estimation in turbo-coded MIMO-OFDM can be also extended to PLC issues (El Chall, 2015). In this regard, it is worthy to extend such techniques for the iterative PLC receivers.

7.5 CS-based strategies

In CS-based approaches, signals and images can only be approximately sparse in practical scenarios; or by applying further techniques such as wavelet shrinkage thresholding (Sermwuthisarn et al., 2012) so that they can be made more sparse. Thus, regarding real PLC applications there is a need for further techniques to transform signals into sparse signals. In Liu et al. (2016a) proposed a novel impulsive noise reduction strategy based on structured CS theory for MIMO OFDM PLC systems. The authors claimed that, by introducing the structured CS theory to impulsive noise recovery; the gap of research-lack on the reduction for MIMO-PLC systems is filled. Another open issue is related to the hardware implementation aspects, where in most of the contributions has not been tackled; hence the need to be considered in the future research.

7.6 SBL-based strategies

Unlike the aforementioned techniques, SBL make use the sparsity information and a priori statistical knowledge of sparse signal's distribution, which makes it a suitable candidate for sparse signals recovery in clean as well as noisy measurement cases. Contrary to the proposed SBL framworks, in Lin et al. (2013) and Korki et al. (2015, 2016), that mainly exploit EM and MAP algorithms. Recently, in Wan et al. (2017) and Arjoune et al. (2017), these hierarchical Bayesian techniques have shown an advantageous balance of small recovery error with fast recovery time. To reduce the computational complexity SBL framworks, a fast alternating algorithm was recently proposed in Dai and So (2018). The authors claimed that the proposed algorithm achieved near-optimal performance at high SNR, compared to that of the state-of-the-art SBL methods, hence the need to be considered in PLC scenarios. More recently, a new variational Bayesian learning algorithm was proposed in Wan et al. (2018), however, its only focusing on recovering the speech signal corrupted by sparse impulsive noise. Thus, it could be extended for OFDM-based PLC signals in future work.

8 Conclusions

PLC is a promising technology that can be an alternative choices for next-generation home networking services and smart grid applications. Over the last years, considerable efforts have been made to standardise NB and BB communications over electrical networks, especially by the international telecommunication union telecommunication and the IEEE communication society. As a matter of fact, impulsive noise represents the most factor impairments for PLC systems, as it comes in bit or burst forms, which can cause degradation of multimedia data transmission. Hence, reducing its impact has gained a huge amount of research interest over the last decade. In this regard, numerous approaches have been proposed to reduce the drastic effects of impulsive noise in PLC systems such as FEC, interleavers, signal processing techniques based on clipping/blanking, iterative suppression algorithms, CS and SBL. Therefore, from a thorough consolidation of related works, this axe of research is very innovative and still open for interesting challenges to be solved. In fact, we suggest that further research on impulsive noise mitigation should tackle, for instance, more robust detection and estimation techniques, complexity and hardware implementations using special nonlinear filters, CS and SBL, and combination of FEC schemes. Besides, image and video transmissions should also be tackled. Finally, investigating combination of non-orthogonal multiplexing transmission framework with massive MIMO for maximising the overall data rates and increasing the penetration of PLC technology in the years to come, sounds very tempting.

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