Impulsive Noise Reduction Techniques in Power Line Communication: A Survey and Recent Trends

Samir Laksir, Abdelaali Chaoub, and Ahmed Tamtaoui
National Institute of Posts and Telecommunications
Lab. STRS, Dep. of Communications Systems
2. Av. Allal El Fassi, Rabat, Morocco
Emails: laksir@inpt.ac.ma, chaoub@inpt.ac.ma, tamtaoui@inpt.ac.ma

***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 indoor network and the ubiquitous sockets (outlets) inside homes and buildings. However, the power-line mediums present challenging task and provide shaky environment for multimedia (audio, image and video) transmission. As a matter of fact, the noise with the highest impact on multimedia transmission is the impulsive noise with disturbances of bursts of errors. Therefore, there has been an intense research in the area of error-mitigation strategies in PLC, thus the need for such a survey. This survey points out the state-of-the-art techniques, and discusses some key questions regarding the current and future trends related to PLC signal protection strategies.**

***Index Terms*—Power line Communication (PLC), Home-networking services, Smart Grid, Impulsive noise reduction.**

I. 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 [1]–[3]. 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 electrical network already installed and the ubiquitous sockets are two revolutionary paradigms of the modern PLC technology, which can provide ubiquitous wired home connectivity as well as an alternative solution for high speed broadband communications using power supply networks.

To promote worldwide PLC deployments, IEEE communication society and International Telecommunication Union - Telecommunication (ITU-T) are the major standards organizations that actively encourage next generation home networking services through power lines, notably by developing standards such as IEEE 1901 [4] and ITU-T G.hn standards [5]. Europe, USA, and Japan are the most active markets regarding standardization and regulation activities [6]. In Europe, for instance, the most relevant such standard is the European Telecommunications Standards Institute (ETSI) and European Norm (EN) 50065. In the USA, PLC emissions are regulated through the Code of Federal Regulations, Title 47, Part 15 (47 CFR chapter 15) by the U.S. Federal Communications Commission (FCC). Furthermore, with the standardization of Multiple-Input Multiple-Output (MIMO) PLC technology [7], increased performance, maximal coverage and double throughput can be achieved which anticipates the move towards ultra-high-speed broadband access and its related services.

Bearing in mind that the electrical supply networks were not natively designed for communication delivery [8], consequently, the low voltage / medium voltage supply networks used as transmission mediums for PLC access systems may act as an antenna producing electromagnetic radiation. Therefore, PLC systems have to ensure very low values regarding the electromagnetic emission and, accordingly, operate with limited signal power levels [9]. On the other hand, 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. These are caused by the high number of branches, varying impedance, and switching transients in the PLC networks. Recent study at the University of Mauritius [10] has shown that the noise with the highest impact on data transmission is impulsive noise and the Narrowband noise has the least effect. Therefore, error-reduction techniques are vital in order to improve performance of PLC systems.

Compared to previous survey articles [11]–[15], this survey mainly presents an overview related to impulsive noise suppression techniques. Firstly, we provide a comprehensive overview related to impulsive noise reduction techniques, including error handling mechanisms, and signal processing based strategies (e.g., time-domain processing, iterative threshold-based, Compressive Sensing (CS), and Sparse Bayesian Learning (SBL)). Secondly, by exploring the literature review, comparison of the existing impulsive noise error-resilient techniques, are outlined. Finally, challenges and future research directions, are suggested.

The rest of the paper is organized as follows. Section II presents an overview on PLC systems. In Section III, we bring an overview on impulsive noise reduction strategies. Comparison of these techniques are provided in Section IV. The challenges and future research directions are given in Section V. Finally, Section VI concludes the survey.

II. An overview on PLC systems

Over the last decades, PLC systems have been increasingly showing great potentials in future home-networking as well as in many smart grid applications [16]. Going beyond the simple enjoyment of high-speed Internet usage or PLC-based Local Area Networks (LANs) networks in buildings, other applications have emerged such as Voice, Video and Multimedia communications, promoted by major alliances namely HomePlug [17] and HD-PLC [18]. As a matter of fact, outdoor Smart Grid services can naturally benefit from the fact that electrical wired infrastructures are already available, thus such services can include Advanced Metering Infrastructure (AMI), Automated Meter Management (AMM), and Automated Meter reading (AMR), services [19]. For instance, Smart Grid applications can provide communication between Plug-in electric vehicles and their charging station, as well as communications between smart appliances such as heaters, air conditioners, washers, and other appliances [20]. Figure 1 shows the current and future indoor PLC architecture schematic.

978-1-5386-4248-1/18/$31.00 ©2018 IEEE

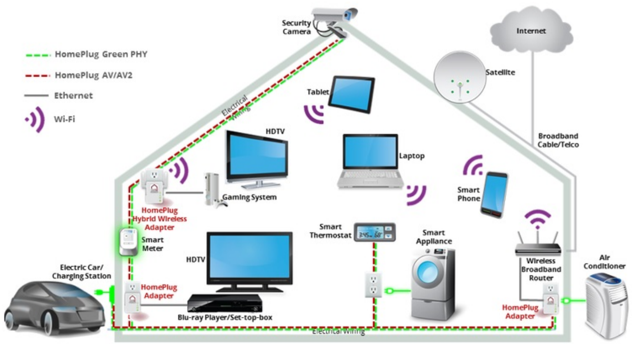

Figure 1. Current and future indoor PLC architecture schematic [17]

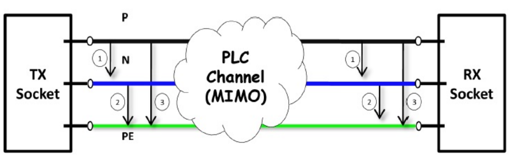

Figure 2. MIMO-PLC channel

The fact that PLC is a costless technology, communication signals are transmitted utilizing the existing (indoor) electrical networks, where the wireless signals can be attenuated and lost such as in under-ground structures and in buildings isolated rooms. Recently, a useful classification of PLC systems according to frequency bands has been introduced in [21]: it distinguishes between ultra-narrowband, Narrowband (NB) and Broadband (BB) PLC systems, operating between about 30-3000 Hz, 3-500 kHz and 1.8-100 MHz, respectively. Basically, PLC systems have long been regarded as a Single Input Single Output (SISO) transmission system based on two conductors between two sockets. This is known as the differential-mode channel between the phase (P) and neutral (N) wires. 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 [21] Chapter 5. Hence, 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). Figure 2 depicts the MIMO-PLC channel for three-wire installations with differential signal feeding through the wires. For instance, in a 2x3 MIMO feeding option, the average capacity gain ranged between 1.8 and 2.2 can be achieved depending on the transmitter's power level [7]. On the other hand, when considered as a transmission medium for communications signals, PLC technology -either SISO or MIMO ones- are subject to various challenges such as high frequency selectivity and multiple additive noises. Basically, there are five commonly known classification of noise types in PLC, as depicted in Figure 3, including colored background noise, narrowband noise, periodic impulsive noise asynchronous or synchronous to the mains frequency (typically $50/60Hz$), and the asynchronous impulsive noise [22]. In fact, three major classes can be distinguished, these are impulsive noise, narrowband noise, and background noise [23].

III. Impulsive noise reduction

This section discusses various approaches to deal with the impulsive structures that occur on PLC channels, or so-called impulsive noise. We first bring impulsive noise reduction methods based on

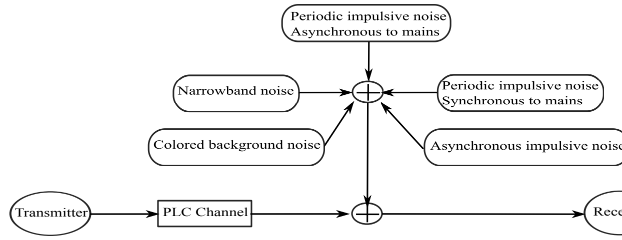

Figure 3. Noises classification in the PLC transmission [22]

error handling strategies, then approaches based on forward error correction and interleaving are presented, and finally signal processing-based strategies are presented. Note that, the theoretical aspects of the investigated techniques are not discussed in this paper, hence for more details the motivated readers are referred to the references therein. Besides, impulsive noise reduction has been 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.

A. Error handling mechanisms

1) Automatic Repeat Request (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 [2]. Furthermore, the legacy ARQ mechanisms are three types of procedure: Send-and-wait, Go-back-N, and Selective reject, and they are specified in IEEE 1901 PLC draft 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 [24]. 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 these reasons, alternative solution such as Hybrid ARQ strategies, that are combinations of ARQ and FEC solutions, can also be suitable to be applied in PLC systems.

2) Forward Error Correction (FEC)-based strategies: Forward Error Correction (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 [25], for instance, popularly used in automatic metering for Narrowband PLC (NB-PLC), has employed a basic convolutional encoder (CE) with bit interleaving to combat narrowband interferences. G3-PLC [26] for smart grid employed both CE and Reed-Solomon (RS) coding in order to mitigate errors caused by background noise and impulsive noise. As for Broadband-PLC (BB-PLC), the IEEE P1901 (FFT-based) [4] 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.

Carrying on with turbo codes (TC), the authors in [27] proposed a TC for single-carrier systems 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 [28], authors analysed the performance of double binary TC over the PLC channel in order to provide a significant gain in OFDM-based PLC systems, whereas the authors in [29] proposed optimum turbo decoding for TC 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.

LDPC coding and decoding for impulsive noise correction was considered in [30] and [31], where the authors shows that LDPC codes are efficient in error correction over Gaussian and impulsive noise channels. In [32], authors asserted that the performance of Quasi-Cyclic LDPC (QC-LDPC) codes can approximate that of the TC with higher block lengths, on typical and realistic PLC channels characteristics. Besides, Figure 5 indicates that, although a TC system provides better error rates at low SNRs, it is significantly outperformed at high SNRs by the QC-LDPC coded system. Additionally, this implementation of QC-LDPC has a simple structure and is easily implementable. In [33], simulation for various QC-LDPC code rates showed that a better performance was achieved with QC-LDPC/RS code combination than that of the QC-LDPC/CE combination, achieving achieving about 1.8 dB improvement at a BER of 10^{-4}.

Other promising Polar Codes (PC) were proposed in [34] and [35]. The authors investigated the performance and robustness of PC for different codeword lengths and noise scenarios in single-carrier and OFDM-based PLC systems. As a matter of fact, authors in [34] asserted that PC are applicable to PLC channels with lower complexity than TC or LDPC. Besides, the result in [35] revealed that PC are efficient in error correction as they achieved a significant code gain compared to LDPC codes while maintaining remarkably lower complexity. Figure 4 shows that PC with soft decision decoding outperforms the conventional LDPC system.

Finally, another FEC scheme called fountain codes [36] for impulsive noise correction in low-voltage indoor PLC were firstly presented in [37], 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 [38], 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.

3) Interleaving techniques: When suddenly impulsive noise occurs, it induces burst errors, hence several blocks of received symbols are corrupted [39]. 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 [40] and G3-PLC standards [26]. In [41], authors proposed a time domain interleaving (TDI) technique aimed at performing the interleaving process post the IFFT. Figure 6 shows that the proposed system is very robust against various impulsive noise scenarios. This is due to 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. In [42], an optimized time-frequency interleaving scheme is proposed, which employs the block size optimization to improve the anti-time-domain impulsive noise capability. Additionally, the proposed scheme using two criteria to maximize the time and frequency diversity is at the symbol level rather than the bit level, which leads to more optimization process and lower implementation complexity, compared to that of the block interleaving scheme.

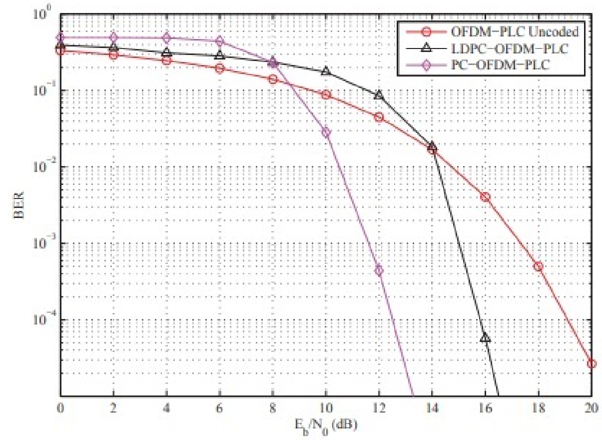

Figure 4. Comparison between PC with LDPC on OFDM-PLC channel, code rate= 0.5 [35]

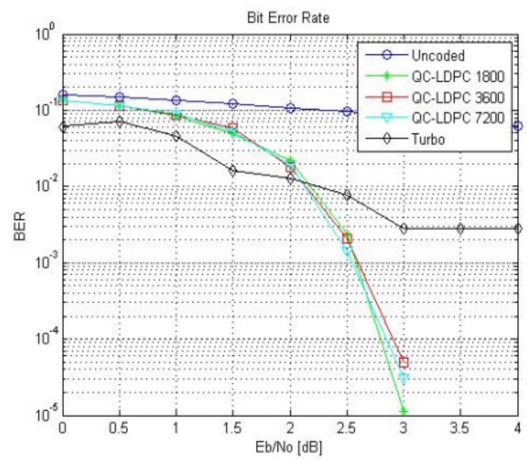

Figure 5. QC-LDPC and Turbo codes for a channel characterized by AWGN and Impulse noise [32]

B. 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.

1) Time-domain techniques: The time-domain techniques [43] (commonly known as non-linear preprocessor techniques), consist in clipping and blanking the high signal amplitudes of the received time-domain signal above a selected threshold value. Figure 7 shows that the best nonlinearity scheme to impulsive noise reduction (in heavily disturbed PLC channel) is the combined clipping/blanking. Several studies have been presented in [44]–[48] in order to improve the performance of non-linear preprocessor techniques. Figure 8 shows the uncoded OFDM transmission using clipping-blanking iterative receiver, while after only two iterations, the performance of the transmission over the AWGN channel is almost achieved. For instance, Ndo et al., in [46], have proposed a threshold optimization based on false alarm and good detection trade-off of the clipping technique. Also, by combining impulse parameters estimation and threshold optimization, they have also proposed an adaptive impulsive reduction scheme for highly and weakly disturbed impulsive noise scenarios. In [47] and [48], authors have introduced techniques to improve clipping/blanking using peak to average power ratio (PAPR)

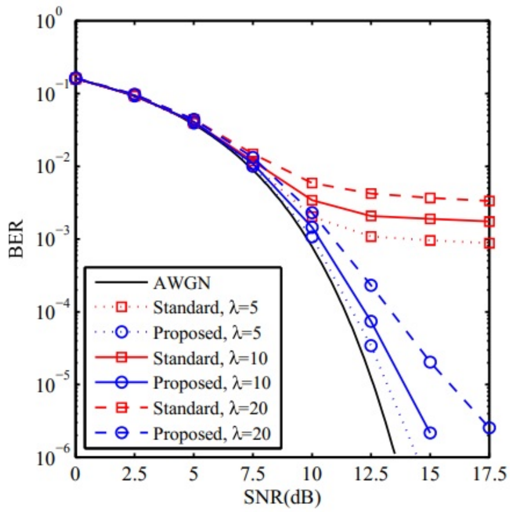

Figure 6. Comparison between proposed TDI with standard interleaver on OFDM-PLC channel [41]

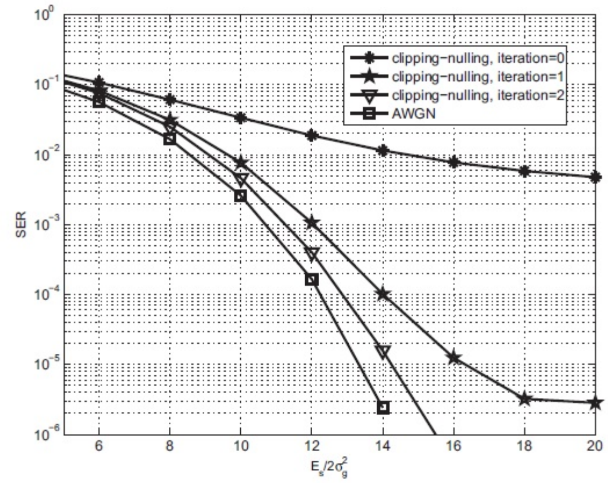

Figure 8. Symbol Error Rate of the iterative 256-OFDM transmission using 4-QAM over the impulsive noise channel [51]

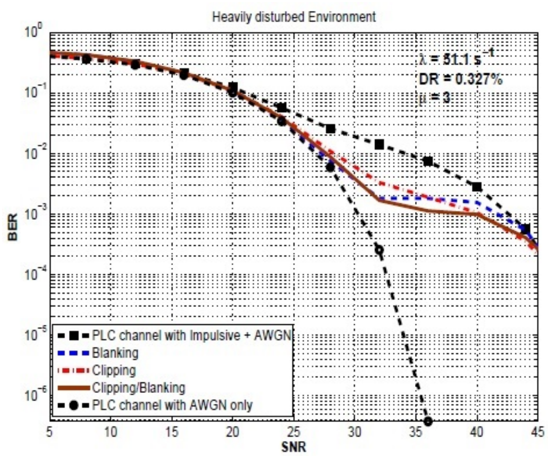

Figure 7. Comparison of time-domain nonlinearity techniques for impulsive noise reduction [43]

based on selective mapping scheme. The authors have claimed that, minimizing the PAPR may also minimize the probability of impulsive noise detection error, allowing improvement up to $3dB$ in terms of SNR when compared to conventional non-linear 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.

Himeur et al., in [49], 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 [50], the same authors have proposed a novel framework that consist of an adaptive noise clipping-based hybrid progressive median filter. 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.

2) Iterative threshold-based algorithms: A more promising approaches have been proposed in [45], [51]–[54], 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 [45], 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 [52] and [53], and to mitigate the effects of impulsive noise on image transmission in OFDM-based PLC in [54] and [55].

3) Time-Frequency domain equalizers: Impulse response shortening filters, i.e., time-domain equalizers (TEQs), have been commonly used in reducing the interblock interference (IBI) by suppressing the tails of the composite impulse response [56]. However, authors in [57], claimed that the presence of impulsive noise in the channel may paralyze 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 [58], FFT-OFDM-based and DWT-OFDM-based PLC systems are studied, and overlap frequency domain equalization (OFDE) as a robust and efficient equalization technique is presented. Moreover, linear precoding (LP) is also suggested for

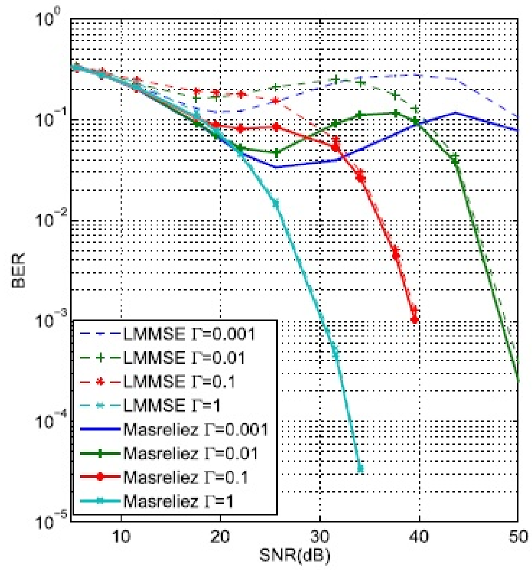

Figure 9. BER performance versus SNR for VOFDM system [51]

FFT and wavelet transformbased 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 equalization models, however, also the LP-based OFDM-OFDE at the expense of slight increment in computational complexity.

C. Soltanpur et al., in [59], have proposed a novel time-domain filter based on Masreliez's approximation in order to equalize the output of the PLC channel. The performance of the filter (nonlinear equalizer) is studied under (Vector) VOFDM system over a multipath PLC in the presence of Middleton Class-A impulsive noise model. Figure 9 shows comparison between Masreliez equalizer for different set of parameters of impulsive noise model with linear minimum mean square error (LMMSE) equalizer. As a matter of fact, the performance of the filter decreases when the impulsive noise and (VOFDM) signal become to close to each other, at higher SNR values.

4) Compressive Sensing (CS)-based strategies: Impulsive noise estimation and removal based on Compressive Sensing (CS) techniques has gained a fast-growing research interest in the context of OFDM based PLC [60]–[64]. 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 [61], 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 minimize the errors of the estimated amplitudes. Furthermore, Al-naffouri et al. in [63], have claimed that the proposed CS algorithms in [60] and [61] make use of l_1 minimization which lead to higher computational costs. In [39], the author has proposed a promising approach to remove the impact of bursty impulsive noise by block-based CS. Similar to the works in [60] and [61], the authors exploited 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 realizations. In [62], the authors 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. Recently, Liu et al., in [64], 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, compared to that of the state-of-art methods. More specifically, the structured CS optimization framework was formulated using spatially multiple measuring method, by fully exploiting the spatial correlation of the impulsive noise signals at different receive antennas.

5) Sparse Bayesian Learning (SBL)-based strategies: Many other low complex approaches have been proposed for impulsive noise estimation and suppression, including Sparse Bayesian Learning (SBL) [65] and block iterative Bayesian algorithm (Block-IBA) [66]. For SBL approach in [65], the authors 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. The frameworks have outperfom the aftermentioned CS-based approaches in terms of BER under diffrent impulsive noise scenarios. Furthermore, Korki et al., in [66] and [67], 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 more promising Block-IBA framework for block-sparse signals based on more realistic impulsive noise model. Additionally, the proposed Bayesian approach differs from [65] 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. Figure 10 shows that the proposed Block-IBA performs better than the other SBL based schemes under two impulsive noise model cases. Lately, conventional direction-of-arrival (DOA) estimation methods in (non-Gaussian) impulsive noise from the perspective of SBL view have been addressed in [68] to deal with different impulsive noise models, including Gaussian mixture model, generalized Gaussian distribution, and -stable distribution. Furthermore, an effective benchmarking study has been conducted.

IV. Comparison of Impulsive Noise Reduction Strategies

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 lower and higher SNRs, since larger power levels make easier the detection and estimation of impulsive noise corrupted samples. As a matter of fact, SBL frameworks perform better than the CS based schemes under PLC channels. On the other hand, time-domain processing techniques (e.g., clipping-blanking and time-domain equalizers) 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 optimization, adaptive impulsive reduction scheme for highly and weakly disturbed impulsive noise scenarios, also provide further noticeable improvements. However, 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 SNRs.

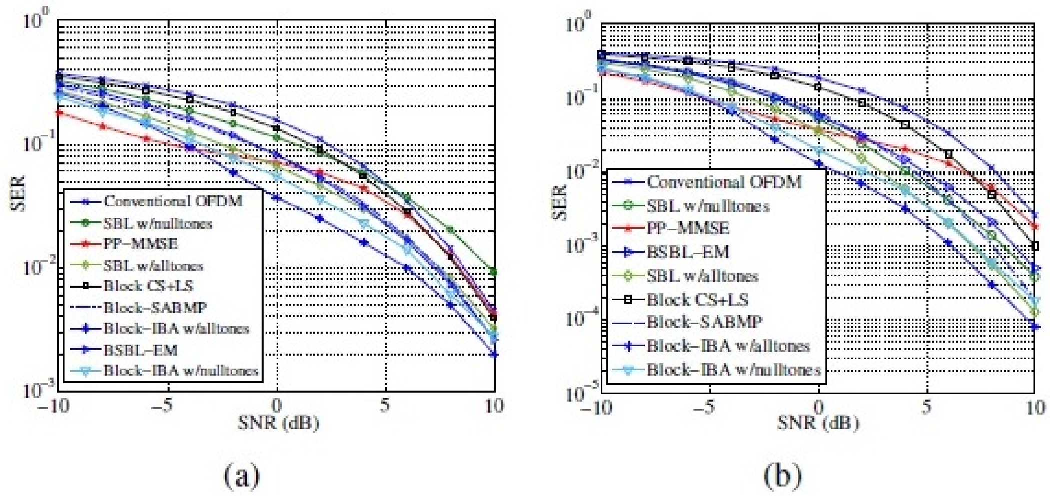

Figure 10. SER performance versus SNR for proposed Block-IBA systems [67]

V. Challenges and future research directions

In this section, we highlight the challenges and future research directions.

A. FEC-based strategies

The main drawbacks of FEC schemes are their higher encoding/decoding complexity and overhead. Therefore, it is crucial to investigate suitable FEC schemes capable of achieving near error free transmission over non-Gaussian impulsive noise. Hence, it is still an open question whether QC-LDPC can perform better that PC (Polar codes) or fountain codes. In future, for instance, to improve the error correction capabilities, interleavers [42] can be combined with fountain codes, or PC can also be combined with QC-LDPC [32] in order to improve the overall performance against the severity of the impulsive noise, considering unequal error protection issues.

B. Modulation techniques

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 [69]. Other alternative digital modulation schemes have been already investigated, these are NOMA [70], spatial modulation (SM) [71], OFDM with index modulation (OFDM-IM [71]), and Golden Angle Modulation (GAM) [72]. It is predicted that, these novel schemes appeared 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. Thus, in future, we strongly suggest the research community to investigate theoretical analysis, practical implementation issues, and demonstrate their possible applications in PLC.

C. Time-domain based strategies

In [73] chapter 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 for noise detection, improved by decorrelating the PLC signal. On the other hand, another solution is to investigate special non-linear filters such as the so-called non-linear equalizer based on Masreliez approximation [59] and the adaptive nonlinear filter based on a canonical piecewise linear (CPWL) approach [74]. Additionally, combination of Masreliez or CPWL filters with powerful decoding FEC schemes (e.g., LDPC or Polar 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.

D. Iterative suppression algorithms

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 [75]. On the other hand, other iterative receiver for MIMO-OFDM systems based on sphere decoding has been shown to have lower average computational complexity [76], while achieving a quasi-ML performance over legacy detection techniques such as MMSE detection and successive interference cancellation schemes. Hence, optimization of the computational complexity of the proposed iterative receivers can also be investigated in order to simultaneously perform the detection and the decoding processes in PLC receivers [76]. Moreover, iterative joint detection and channel estimation in Turbo-Coded MIMO-OFDM can be also extended to PLC issues.

E. CS-based impulsive noise reduction

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 [77] 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. Liu et al., in [64], 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, hence the need to be considered in the future research.

F. SBL-based impulsive noise reduction

Unlike the aforementioned SBL techniques. Recently, in [78], Hierarchical Bayesian techniques have shown an advantageous balance of small recovery error with fast recovery time. In [68], the authors claimed that a fast alternating SBL algorithm achieved near-optimal performance, compared to that of the state-of-the-art SBL methods, hence the need to be considered in PLC scenarios.

G. Other future research directions

Firstly, through the previous section, a few papers investigated the computational complexity of their proposed schemes. Secondly, most 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.

VI. Conclusion

The use of the electrical network already installed and the ubiquitous sockets are two revolutionary paradigms of the modern Power Line Communication (PLC) technology. Therefore, it can be considered as an alternative choices for next-generation home networking services and smart grid applications. In 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 in PLC systems. Hence, reducing its impact has gained a huge amount of research interest over the last decade. In this paper, we have highlighted numerous approaches such as forward error correction, interleaving, and signal processing based-techniques. Additionally, comparisons of the existing impulsive noise error-resilient techniques have been presented. On top of that, we suggest that further research on impulsive noise reduction in PLC may tackle, for instance, special non-linear filters, structured compressive sensing theory, and Hierarchical Bayesian techniques. Moreover, polar codes and quasi-cyclic LDPC schemes have shown better error correction, hence the need to be considered in PLC standards. Finally, investigating combination of non-orthogonal multiplexing techniques with multiple-input multiple-output techniques for maximizing the overall data rates and increasing the penetration of PLC technology in the years to come, sounds to be very tempting.

Finally, our future work would be seeking the fundamental theoretical aspects and simulated comparison of different discussed techniques to investigate their strengthens and weaknesses. Besides, application to image transmission over noisy PLC channels using error-mitigation strategies will be investigated.

References

[1] M. Gotz, M. Rapp, and K. Dostert, “Power line channel characteristics and their effect on communication system design,” *IEEE Communications Magazine,* vol. 42, issue 4, pp. 78-86, Apr. 2004.

[2] H. Hrasnica, A. Haidine and & R. Lehnert, “Broadband powerline communications: network design,” John Wiley & Sons, 2005.

[3] N. Pavlidou, A. H. Vinck, J. Yazdani, & B. Honary, “Power line communications: state of the art and future trends,” IEEE Communications magazine, vo. 41, no. 4, pp. 34-40, 2003.

[4] —, “IEEE standard for broadband over power line networks: medium access control and physical layer specifications,” IEEE Std 1901, 2010, vol. 2010, pp. 1-1586.

[5] M. M. Rahman, C. S. Hong, J. Lee, M. A. Razzaque, & J. H. Kim, “Medium access control for power line communications: An overview of the IEEE 1901 and ITU-T G.hn standards,” IEEE Commun. Mag, vol. 49, no. 6, pp. 183191, 2011.

[6] J. Lampe, “Power Line Communications: Principles, Standards and Applications from multimedia to smart grid,” John Wiley & Sons, 2016.

[7] L. T. Berger, A. Schwager, P. Pagani, & D. M. Schneider, “MIMO power line communications,” IEEE Communications Surveys & Tutorials, vol. 17, no. 1, pp. 106-124, 2015.

[8] J. Anatory, M. V. Ribeiro, A. M. Tonello, & A. Zeddam “Power-line communications: smart grid, transmission, and propagation,” Journal of Electrical and Computer Engineering, vol. 2013, 2013.

[9] Calculated impact of PLC on Stations Operating in the Amateur Radio Service. http://www.arrl.org/files/file/bpl/C63NovPLC.pdf. Accessed 23 October 2017

[10] B. Rajkumarsingh and B.N. Sokappadu, “Noise Measurement and Analysis in a Power Line Communication Channel, ” In International Conference on Emerging Trends in Electrical, Electronic and Communications Engineering ,pp. 81-93, Springer, Cham, 2016, November.

[11] G. Laguna, and R. Barron, “Survey on indoor power line communication channel modeling,” In Electronics, Robotics and Automotive Mechanics Conference, 2008. CERMA’08 (pp. 163-168). IEEE.

[12] N. Sharma, T. Pande & M. Shukla, “Survey of power line communication,” IJCA, CSI-COMNET, 2011.

[13] X. Fang, S. Misra, G. Xue, & D0 Yang, (2012). Smart grid - The new and improved power grid: A survey. IEEE communications surveys & tutorials, vol. 14, no. 4, pp. 944-980, 2012.

[14] A. O. Peter, “Power Line Communication (PLC) impulsive noise mitigation: A review,” 2014

[15] C. Cano et al., “State of the art in power line communications: From the applications to the medium,” IEEE Journal on Selected Areas in Communications, vol. 34, no. 7, pp. 1935-1952, 2016.

[16] S. Galli and O. Logvinov, “Recent developments in the standardization of power line communications,” IEEE Communications Magazine, vol. 46, no. 7, pp. 64-71, 2008.

[17] Homeplug powerline alliance website. http://www.homeplug.org/. Accessed 23 October 2017.

[18] HD-PLC alliance website. www.hd-plc.org. Accessed 23 October 2017.

[19] S. Galli, A. Scaglione, & Z. Wang, “For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid,” in Proceedings of the IEEE, vol. 99, no. 6, pp. 998-1027, 2011.

[20] K. Sharma, and L. M. Saini, “Power-line communications for smart grid: Progress, challenges, opportunities and status,” Renewable and Sustainable Energy Reviews, 2017, vol. 67, p. 704-751.

[21] L.T. Berger, A. Schwager, P. Pagani, & D. Schneider, (Eds.) “MIMO power line communications: narrow and broadband standards, EMC, and advanced processing,” CRC Press, 2014.

[22] M. Zimmermann and K. Dostert, “Analysis and modeling of impulsive noise in broad-band powerline communications,” IEEE transactions on Electromagnetic compatibility, vol. 44, no. 1, pp. 249-258, 2002.

[23] V. Degardin, M. Lienard, A. Zeddam, F. Gauthier, & P. Degauquel, “Classification and characterization of impulsive noise on indoor powerline used for data communications,” IEEE Transactions on Consumer Electronics, vol. 48, no. 4, pp. 913-918, 2002.

[24] H. Chen, R. G Maunder, & L. Hanzo, “A survey and tutorial on low-complexity turbo coding techniques and a holistic hybrid ARQ design example,” IEEE Communications Surveys & Tutorials, vol. 15, no. 4, pp. 1546-1566, 2013.

[25] PRIME White Paper. http://www.prime-alliance.org/?$page_i d = 3376$. Accessed 23 October 2017.

[26] K. Razazian et al., “G3-PLC specification for powerline communication: Overview, system simulation and field trial results,” In Power Line Communications and Its Applications (ISPLC), 2010 IEEE International Symposium on (pp. 313-318). IEEE.

[27] D. F. Tseng, T. R. Tsai, & Y. S Han, “Robust turbo decoding in impulse noise channels,” In Power Line Communications and Its Applications (ISPLC), 2013 17th IEEE International Symposium on (pp. 230-235). IEEE.

[28] E. C. Kim et al., “Performance of double binary turbo coding for high speed PLC systems,” IEEE Transactions on Consumer Electronics, vol. 56, no. 3, 2010.

[29] Umehara, D., Yamaguchi, H., & Morihiro, Y. (2004, November). Turbo decoding in impulsive noise environment. In Global Telecommunications Conference, 2004. GLOBECOM’04. IEEE (Vol. 1, pp. 194-198). IEEE.

[30] Ardakani, M., Kschischang, F. R., & Yu, W. (2005, April). Low-density parity-check coding for impulse noise correction on power-line channels. In Power Line Communications and Its Applications, 2005 International Symposium on (pp. 90-94). IEEE.

[31] O. Hui-Myoung et al., “Mitigation of performance degradation by impulsive noise in LDPC coded OFDM system,” In Power Line Communications and Its Applications, 2006 IEEE International Symposium on (pp. 331-336). IEEE.

[32] Prasad, G., Latchman, H. A., Lee, Y., & Finamore, W. A. A comparative performance study of ldpc and turbo codes for realistic plc channels. In Power Line Communications and its Applications (ISPLC), 2014 18th IEEE International Symposium on (pp. 202-207). IEEE.

[33] N. Andreadou and F. N. Pavlidou, “Mitigation of impulsive noise effect on the PLC channel with QCLDPC codes as the outer coding scheme,”

IEEE Transactions on Power Delivery, vol. 25, no. 3, pp. 1440-1449, 2010.

[34] J. Jin et al., "Performance of polar codes with successive cancellation decoding over PLC channels," In Power Line Communications and its Applications (ISPLC), 2015 International Symposium on (pp. 24-28).

[35] Hadi, A., Rabie, K. M., & Alsusa, E. (2016, July). Polar codes based OFDM-PLC systems in the presence of middleton class-A noise. In Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2016 10th International Symposium on (pp. 1-6). IEEE.

[36] Cheng, L., Swart, T. G., & Ferreira, H. C. (2013, March). Adaptive rateless permutation coding scheme for OFDM-based PLC. In Power Line Communications and Its Applications (ISPLC), 2013 17th IEEE International Symposium on (pp. 242-246). IEEE.

[37] P. Amirshahi, S. M. Navidpour, & M. Kavehrad, "Fountain codes for impulsive noise correction in low-voltage indoor power-line broadband communications," In Consumer Communications and Networking Conference, 2006. CCNC 2006. 3rd IEEE (Vol. 1, pp. 473-477).

[38] M. Luby et al., "High-quality video distribution using power line communication and aplication layer forward error correction," In Power Line Communications and Its Applications, ISPLC'07. IEEE International Symposium on (pp. 431-436), 2007.

[39] L. Lampe, "Bursty impulse noise detection by compressed sensing," In Power Line Communications and Its Applications (ISPLC), 2011 IEEE International Symposium on, pp. 29-34. April 2011.

[40] J. LeClare et al., "An Overview, History, and Formation of IEEE P1901.2 for Narrowband OFDM PLC," https://www.maximintegrated.com/en/app-notes/index.mvp/id/5676. Accessed 23 October 2017.

[41] A. Al-Dweik et al. "Efficient interleaving technique for OFDM system over impulsive noise channels," In Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on (pp. 167-171).

[42] S. Liu, F. Yang & J. Song, "An optimal interleaving scheme with maximum time-frequency diversity for PLC systems," IEEE Transactions on Power Delivery, vol. 31, no. 3, pp. 1007-1014, 2016.

[43] K. S. Al-Mawali et al., "Time-domain techniques for impulsive noise reduction in OFDM-based power line communications: A comparative study," In International Conference on Communication, Computer and Power (ICCCP 2009) (pp. 368-372).

[44] K. S. Al-Mawali et al., Joint time-domain/frequency-domain impulsive noise reduction in OFDM-based power line communications. In Telecommunication Networks and Applications Conference, 2008. ATNAC 2008. Australasian (pp. 138-142). IEEE.

[45] S. V. Zhidkov, "Analysis and comparison of several simple impulsive noise mitigation schemes for OFDM receivers," IEEE Transactions on Communications, vol. 56, no. 1, 2008.

[46] G. Ndo, P. Siohan & M. H. Hamon, "Adaptive noise mitigation in impulsive environment: Application to power-line communications," IEEE Transactions on Power Delivery, vol. 25, no. 2, 647-656, 2010.

[47] K. M. Rabie, and E. Alsusa, "Improving blanking/clipping based impulsive noise mitigation over powerline channels," In Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on (pp. 3413-3417). IEEE, 2013.

[48] K. M. Rabie and E. Alsusa, "Preprocessing-based impulsive noise reduction for power-line communications," IEEE Transactions on Power Delivery, vol. 29, no. 4, pp. 1648-1658, 2014.

[49] Y. Himeur and A. Boukabou, "OFDM-based power-line communication enhancement using a turbo coded adaptive impulsive noise compensator," Telecommunication systems, vol. 62, no .3, pp. 481-494, 2017.

[50] Y. Himeur and A. Boukabou, "Robust image transmission over powerline channel with impulse noise," Multimedia Tools and Applications, vol. 76, no. 2, pp. 2813-2835, 2017.

[51] A. Mengi and A. H. Vinck, "Successive impulsive noise suppression in OFDM," In Power Line Communications and Its Applications (ISPLC), 2010 IEEE International Symposium on (pp. 33-37).

[52] X. Hu, Z. Chen, & F. Yin, "Impulsive noise cancellation for MIMO power line communications. Journal of Communications," vol. 9, no. 3, pp. 241-247, 2014.

[53] M. R. Ahadiat, P. Azmi & A. Haghbin, "Impulsive noise estimation and suppression in OFDM systems over in-home power line channels," International Journal of Communication Systems, vol. 30, no. 1, 2014.

[54] S. Laksir and A. Tamtaoui "Reduction of the effect of impulsive noise on image transmission in OFDM-based power line communications," In Information Technology for Organizations Development (IT4OD), 2016 International Conference on (pp. 1-6).

[55] S. Laksir, A. Chaoub & A. Tamtaoui, "Iterative algorithms for impulsive noise reduction in OFDM-based power line communications," Int. J. Embedded Systems. (In press).

[56] S. Celebi "Interblock interference (IBI) minimizing time-domain equalizer (TEQ) for OFDM," IEEE Signal Processing Letters, vol. 10, no. 8, pp. 232-234, 2003.

[57] Y. C. Tan, N. B. Ramli & T. C. Chuah, "Time-domain equalizer for multicarrier systems in impulsive noise," International Journal of Communication Systems, vol 25, no. 2, pp. 111-120, 2012.

[58] A. Khan and S. Y. Shin, "Linear precoded wavelet OFDM-based PLC system with overlap FDE for impulse noise mitigation," International Journal of Communication Systems, vol. 30, no. 17, 2017.

[59] C. Soltanpur, K. M. Rabie, B. Adebisi, & A. Wells, "Masreliez-Equalized VOFDM in Non-Gaussian Channels: Power Line Communication Systems," IEEE Systems Journal, 2017.

[60] G. Caire, T. Y. Al-Naffouri & A. K. Narayanan, "Impulse noise cancellation in OFDM: An application of compressed sensing," In Information Theory, 2008. ISIT 2008. IEEE International Symposium on (pp. 1293-1297). IEEE.

[61] Al-Naffouri, T. Y., Quadeer, A. A., & Caire, G. (2011, July). Impulsive noise estimation and cancellation in DSL using orthogonal clustering. In Information Theory Proceedings (ISIT), 2011 IEEE International Symposium on (pp. 2841-2845). IEEE.

[62] A. Mehboob, L. Zhang & J. Khangosstar, "Adaptive impulsive noise mitigation using multi mode compressive sensing for powerline communications," In Power Line Communications and Its Applications (ISPLC), 2012 16th IEEE International Symposium on (pp. 368-373). IEEE.

[63] T. Y. Al-Naffouri, A. A. Quadeer & G. Caire, "Impulse noise estimation and removal for OFDM systems," IEEE Transactions on Communications, vol. 62, no. 3, pp. 976-989,2014.

[64] S. Liu et al. "Impulsive Noise Cancellation for MIMO-OFDM PLC Systems: A Structured Compressed Sensing Perspective," In Global Communications Conference (GLOBECOM), 2016 IEEE (pp. 1-6).

[65] J. Lin, M. Nassar, & B. L. Evans, "Impulsive noise mitigation in powerline communications using sparse Bayesian learning," IEEE Journal on Selected Areas in Communications, vol. 31, no. 7, pp. 1172-1183, 2013.

[66] M. Korki et al. "An iterative Bayesian algorithm for block-sparse signal reconstruction," In Acoustics, Speech and Signal Processing (ICASSP), 2015 IEEE International Conference on (pp. 2174-2178). IEEE.

[67] M. Korki, J. Zhangy, C. Zhang, & H. Zayyani, "Block-Sparse Impulsive Noise Reduction in OFDM SystemsA Novel Iterative Bayesian Approach," IEEE Transactions on Communications, vol. 64, no. 1, pp. 271-284, 2016.

[68] J. Dai and H. c. So, "Sparse Bayesian Learning Approach for Outlier-Resistant Direction-of-Arrival Estimation," IEEE Transactions on Signal Processing, vol. 66, no. 3, pp. 744-756, 2018.

[69] K. M. Rabie et al., "A Comparison Between Orthogonal and Non-Orthogonal Multiple Access in Cooperative Relaying Power Line Communication Systems," IEEE Access, vol. 5, pp. 10118-10129, 2017.

[70] Z. Ding, M. Peng, & H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," IEEE Communications Letters, vol. 19, no. 8, pp. 1462-1465, 2015.

[71] E. Basar et al., "Index modulation techniques for next-generation wireless networks," IEEE Access, vol. 5, pp. 16693-16746, 2017.

[72] P. Larsson, "Golden angle modulation," IEEE Wireless Communications Letters, 2017.

[73] S. V. Vaseghi, "Advanced digital signal processing and noise reduction," John Wiley & Sons, 2008.

[74] J. Zhai et al. "A modified canonical piecewise-linear function-based behavioral model for wideband power amplifiers," IEEE Microwave and Wireless Components Letters, vol. 26, no. 3, pp. 195-197, 2016.

[75] H. L. Van Trees, "Optimum array processing: Part IV of detection, estimation, and modulation theory," John Wiley & Sons, 2004.

[76] R. El Chall, "Iterative receiver for MIMO-OFDM systems based on sphere decoding: convergence, performance and complexity tradeoffs," (Doctoral dissertation, INSA de Rennes), 2015.

[77] P. Sermwuthisarn et al., "Impulsive noise rejection method for compressed measurement signal in compressed sensing," EURASIP Journal on advances in signal processing, vol. 68, no. 1, 2012.

[78] Y. Arjoune, N. Kaabouch, H. El Ghazi, & A. Tamtaoui, "Compressive sensing: Performance comparison of sparse recovery algorithms," In Computing and Communication Workshop and Conference (CCWC), 2017 IEEE 7th Annual (pp. 1-7). IEEE.