Subcarrier and Interleaver Assisted Burst Impulsive Noise Mitigation in Power Line Communication

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SUMMARY Impulsive noise (IN) is the most dominant factor degrading the performance of communication systems over powerlines. In order to improve performance of high-speed power line communication (PLC), this work focuses on mitigating burst IN effects based on compressive sensing (CS), and an adaptive burst IN mitigation method, namely combination of adaptive interleaver and permutation of null carriers is designed. First, the long burst IN is dispersed by an interleaver at the receiver and the characteristic of noise is estimated by the method of moment estimation, finally, the generated sparse noise is reconstructed by changing the number of null carriers (NNC) adaptively according to noise environment. In our simulations, the results show that the proposed IN mitigation technique is simple and effective for mitigating burst IN in PLC system, it shows the advantages to reduce the burst IN and to improve the overall system throughput. In addition, the performance of the proposed technique outperforms other known nonlinear noise mitigation methods and CS methods.

**key words:** power line communication, CS, impulsive noise, OFDM, null carrier, noise mitigation

1. **Introduction**

Power line communications (PLC), which reuses power lines for the purpose of data communications has attracted considerable attention for supporting smart grid applications. Smart grid refers to cyber physical system that will utilize modern communication technologies intelligently manage energy transmission and distribution, it maximizes the operational efficiency of energy production, transmission, and delivery. PLC is particularly appealing for smart grid applications since it offers communication capability in an easy and simple deployment [1]; it can exchange status information over different network nodes. As the power lines were originally designed for AC power distribution, it is not well suited for communication signals [2]. There are ongoing debates whether PLC can become the alternative of already-in-market wireless technology or not; however, there is no doubt that PLC is the supplement of wireless communication in smart grid as it offers the existing communication link. In order to improve the reliability of PLC, it is essential to overcome a number of inherent challenges, such as frequency-selective fading and impulsive noise (IN). IN is generated due to the switching transients of electrical appliances and can be classified into three main types [3]: periodic IN asynchronous to the mains frequency, periodic IN synchronous to the mains frequency and asynchronous IN interferences. Most of all, asynchronous IN is the most dominant factor that degrades the communication signals, it varies from few microseconds to milliseconds in its duration. In order to overcome the effect of the IN from PLC channel, several techniques such as noise blanking, clipping [4] and filtering techniques [5] with different degrees of complexity have been proposed in early literature. However, threshold values and filter parameters of these techniques are determined according to practical experience and are not suitable for time-varying channel conditions [6]. On the other hand, channel coding is used to cope with various noises and thereby promote the data detection performance [7], however, the complexity of these ways increased with the length of code exponentially [8]. Some sophisticated signal processing techniques that use null carriers (NC) to estimate noise [9] have been developed, they consider IN as sparse signal in time and using recently developed algorithms for sparse signal reconstruction [10]. Unfortunately, the disturbance ratio (number of impulses) of the IN changes considerably in practical systems [11], so it wastes a lot of carrier resource and result in low throughput when use fixed null carriers. Moreover, in some cases, the duration of IN may become substantially longer than the OFDM symbol duration, it will make a lot of error bits and the system’s performance may be severely degraded [12].

In this paper, we exploit the fact that IN projected onto a signal-free subspace is sparse to estimate the locations and amplitudes of the IN at the receiver [13]. For the sake of making the long duration of burst IN sparse, a special interleaver is enabled to distribute IN across several OFDM blocks. Method of moment estimation is used to estimate the characteristic parameters of the sparse IN. In order to improve the BER and throughput of the system, we propose to increase or decrease the number of null carriers (NNC) and length of interleaver (LI) according to the state information of IN. Therefore, the contribution of this paper are as follows: First, an adaptive IN mitigation system is proposed, which can achieve the performance balance in weak and heavy IN environment by changing NNC and LI adaptively.
Second, a prior auxiliary threshold for selecting the prior support set of IN is designed. In this mechanism, the threshold can be calculated based on the noise parameters estimated by the moment estimation. The results show that the proposed method not only improve the BER performance of the communication, but also achieves a higher throughput between the transmitter and the receiver according to the characteristics of the IN.

The rest of this paper is organized as follows. In Sect. 2, we measure and analyze the IN generated by indoor household appliances. In Sect. 3, the IN-mitigation technique is proposed based on CS and interleaver. A detailed discussion of IN-mitigation technique is presented in Sect. 4. The simulation results are presented in Sect. 5. Finally, conclusions are drawn in Sect. 6.

2. Analysis of Power Line IN

In order to analyze the characteristics of IN on power line, it is necessary to test the actual IN [14]. In this paper, the IN was tested on the 7th floor laboratory of electric institute of Hunan university. The main instruments used to test are Pico 5243B oscilloscope, power carrier communication coupler and filter power supply.

Figure 1 is the time-domain and frequency-domain waveform of IN measured when the fluorescent lamp and electric oven are turned on in the laboratory. Figure 1 (a) is time-domain pulse waveform obtained from indoor measurement. The left and right sides are the measured pulse waveform when the fluorescent lamp and the electric oven opened respectively. The amplitude of the two kinds of IN is far beyond the background noise and its duration can reach hundreds of microseconds with the characteristics of burst. Figure 1 (b) is a figure of power spectral density of various IN. It can be seen from the diagram that the power spectral density of IN is generally higher than that of background noise about 10-25 dB, all of them will have a greater impact on the power line communication performance. Therefore, it is necessary to design noise suppression algorithm to suppress IN.

3. Proposed IN Mitigation Scheme

In order to suppress the IN on power line, the paper designs the communication system based on transmitter and receiver. Figure 2 is a detailed block diagram of the proposed IN-mitigation system. At the transmitter, the information bits are processed by IFFT modulator and interleaver, the NNC and LI are adjusted by feedback information, each OFDM symbol passes through power line channel contaminated by IN and background noise. At the receiver, the system is constituted of several major sub-blocks: deinterleaving block, IN estimation block and IN reconstruction block. Here, \( p \) and \( \hat{e}_{cs} \) are the probability and CS estimation of IN respectively.

3.1 Transmitter Design

At the transmitter, the communication system is consider as a conventional orthogonal frequency division multiplexing (OFDM) transmission system based on inverse discrete Fourier transform (IDFT). First, binary data stream are mapped into QPSK data symbol \( d = [d_1, d_2, \ldots, d_M]^T \) using 4 alternative symbols, \( M \) is the total number of data subcarriers used in a block. As there are some subcarriers forbidden to use in some communication case, we use these subcarriers as NC to estimate IN by CS technology. To make a complete OFDM block of dimension \( N \times 1 \), each OFDM block insert \( N - M \) NC, so \( d \) is expanded to a \( N \) dimensional
In addition, an IN mitigation method based on CS is used to reconstruct the burst IN, an optimal reconstruct threshold is designed with the estimated parameters for accurate recovery of IN. Further more, the NNC and LI are adjusted according to the IN characteristics parameters to improve the utilization rate of null subcarriers and to enhance the sparsity of burst IN respectively.

4. Adaptive IN Mitigation

4.1 IN Dispersion Using Interleaver

In the early literature, the noise model used for simulation is the classical noise model that the amplitude of IN is sparse. However, the results measured in Sect. 2 show that the average duration of impulse burst is one or two symbols of the OFDM symbol. In these cases, it is not practical to consider IN as sparse signal and the reconstruction of IN will be inaccurate [17]. To mitigate IN with long duration, it is necessary to change the structure of burst IN in transmitter and receiver to make IN more sparse. To meet this requirement, a random block interleaver with N rows and LI columns is adopted to permute the columns of the interleaver randomly. When there is long burst IN, the interleaver can disperse the IN as evenly as possible. In addition, the interleaver is designed to guarantee the data symbols transmitted by the same subchannel will not permuted into the same data block.

As shown in Fig. 3, left is an interleaver block that contaminated by IN in time domain, some of the OFDM symbols are interfered totally by burst IN, it is difficult for CS to reconstruct impulse from such signals. So an interleaveing operation is adapted on each subcarrier as the following expression

\[ l' = (l + m) \mod LI \]

where \( l \) represents the \( l \)th position of each row, \( m \) represents the \( m \)th row of the interleaver, \( l' \) is the new position of the corresponding element. After interleaving, the burst IN is spread out to different locations of the interleaver. For example, the IN in the 1th and 2nd position of the first row are moved randomly to the 5th and 8th position, respectively. Similarly, the 1th, 3th and 5th position of the 4th
row are distributed randomly to the 7th, 1th and 9th position, respectively. With the spread effect of permutation, each de-interleaved OFDM symbol have less number of successive impulses, so it will be easier for CS algorithm to reconstruct IN. In addition, when experiencing time-varying background noise and IN over the indoor PLC channels, it is feasible to adjust the size of the interleaver by selecting a corresponding LI from a look up table.

4.2 Characteristics Parameters Estimation of IN

As shown in Fig. 2, after receiving the signal, the receiver first deinterleaves the received signal. To analyze the time-varying IN, the moment estimation method is used to estimate the interference rate and power parameters of IN. \( \sigma_1^2 \) is assumed to be the power of transmitted signal that include no impulsive noise and background noise, \( \sigma_2^2 \) denotes the power of the IN, and \( \sigma_w^2 \) is the power of background noise. In addition, \( \sigma_1^2 = \sigma_2^2 + \sigma_w^2 \) equals to the power of the received signal without occurrence of IN, and \( \sigma_2^2 = \sigma_1^2 + \sigma_w^2 + \sigma_i^2 \) equals to the power of the received signal with occurrence of IN. The probability of IN that needs to be estimated is \( p \).

The expected value of the received signal \( r_k \) is estimated by \( A, B, C \) using a multi-order moment [18]. The expression of the received signal estimation is as follows:

\[
A = E(r_k) = \sqrt{\frac{2}{\pi}} (1 - p) \sigma_1 + p \sigma_2, \quad (6)
\]

\[
B = E(r_k^2) = (1 - p) \sigma_1^2 + p \sigma_2^2, \quad (7)
\]

\[
C = E(|r_k|^3) = \frac{4}{\sqrt{2\pi}} [(1 - p) \sigma_1^3 + p \sigma_2^3], \quad (8)
\]

where \( E(\cdot) \) denotes the expectation. Let \( a = A \sqrt{2\pi}, b = B, c = A \sqrt{2\pi} C \), the expression above can be rewritten as

\[
a = (1 - p) \sigma_1 + p \sigma_2, \quad (9)
\]

\[
b = (1 - p) \sigma_1^2 + p \sigma_2^2, \quad (10)
\]

\[
c = (1 - p) \sigma_1^3 + p \sigma_2^3, \quad (11)
\]

Combining (9)–(11), yields

\[
\sigma_1 = \frac{ab - c + \sqrt{(ab - c)^2 - 4(a^2 - b)(b^2 - ac)}}{2(a^2 - b)}, \quad (12)
\]

\[
\sigma_2 = \frac{ab - c - \sqrt{(ab - c)^2 - 4(a^2 - b)(b^2 - ac)}}{2(a^2 - b)}. \quad (13)
\]

The expressions (12) and (13) satisfy the following conditions

\[
\begin{align*}
(a^2 - b) & \neq 0 \\
(ab - c)^2 - 4(a^2 - b)(b^2 - ac) & > 0.
\end{align*}
\]

In practical, the simplest method to obtain \( a, b, \) and \( c \) is compute the following expressions over \( M \) observations

\[
a = \sqrt{\frac{\pi}{2}} \left( \frac{1}{M} \sum_{k=1}^{M} |r_k| \right), \quad (15)
\]

\[
b = \frac{1}{M} \sum_{k=1}^{M} r_k^2, \quad (16)
\]

\[
c = \frac{\sqrt{2\pi}}{4} \left( \frac{1}{M} \sum_{k=1}^{M} |r_k|^3 \right). \quad (17)
\]

Finally, combining (9)–(11) and (12)–(13), yields

\[
\hat{p} = \frac{\sigma_1 - a}{\sigma_1 - \sigma_2}, \quad (18)
\]

\[
\hat{\mu} = \frac{\sigma_1^2}{\sigma_2^2} = \frac{\sigma_2^2 - \sigma_i^2}{\sigma_w^2}. \quad (19)
\]

It can be seen from the expression above that the characteristics \( (\hat{p} \text{ and } \hat{\mu}) \) of IN can be easily derived by the estimation of a number of OFDM symbols. So it is easy to determine whether the channel is heavily disturbed or not. Using the estimated parameters \( \hat{p} \) and \( \hat{\mu} \), the system can adjust the NNC and LI to suppress the noise introduced by power line channel. Figure 4 depicts the difference between the real \( p \) and estimated \( \hat{p} \) values when the number of IN varies in an alternating voltage (AC) cycle, and LI is fixed at 20. It is observed that the estimated \( \hat{p} \) value approaches the actual \( p \) value when the number of IN changes from 1 to 11. Therefore, it is reasonable to use the estimated \( \hat{p} \) value instead of the real \( p \) value when there are only a few burst IN in an (AC) cycle.

According to previous studies [19], the state of IN can be divided into three types based on the parameters \( p \) and \( \mu \):
1) heavily disturbed \((p = 0.25 \text{ and } \mu = 1000)\), 2) moderately disturbed \((p = 0.1 \text{ and } \mu = 100)\) and 3) weakly disturbed \((p = 0.01 \text{ and } \mu = 10)\). In the following sections, this classification has been used to analyse and simulate the performance result of the proposed algorithm.

### 4.3 Reconstruction of IN Using CS

As shown in Fig. 2, after being interleaved by the interleaver, the received signal \(r\) become a sparse signal, so it is possible to reconstruct IN by using compression sensing method. To reconstruct IN, the received signal \(r\) is transformed by Fourier transform and can be expressed as

\[
y = Fr = FHx + Fz + Fe
\]

\[
= FHF^H S \cdot d + z' + i'
\]

\[
= Dd' + z' + i'
\]

(20)

Where \(D = FHF^H = \begin{bmatrix} H_0 & H_1 & \cdots & H_{N-1} \end{bmatrix}\) is a diagonal matrix, \(H_k = \sum_{i=0}^{L-1} h_i e^{-j \frac{2 \pi k i}{N}}\), \(k \in (0, 1, \ldots, N - 1)\), \(z'\) can be considered as Gaussian noise and \(i'\) is the IN after DFT. If there is no IN and background noise, the transmitted data can be easily recovered using the element-by-element relationship,

\[
d' = D^{-1} y
\]

In contrary, when there is IN during transmission process, the whole OFDM block will be affected and the recovery of the OFDM block becomes difficult. Therefore, null carriers is used to estimate IN and IN-mitigation method based on CS is adopted to cancel the IN from the received signal. For the sake of simplicity, we use \(S\) denotes a \(K \times 1\) vector obtained from the received data, \(e\) is a \(N \times 1\) sparse IN signal and \(\xi\) is a stochastic random process. Take the CS measurement model into account, the problem of (24) is transformed into estimating an optimum sparse vector \(e\) contaminated by \(\xi\) and can be expressed as

\[
\min_{e, \xi} \|e\|_1 \text{subject to } \|\hat{\theta} - F_1 e, \xi\|_2 \leq \epsilon
\]

(25)

Where \(\epsilon\) is not bigger than the noise level \(\sigma_y^2\), \(e, \xi\) is the CS estimation of IN. As the characteristic parameters of IN can be obtained, the IN cancellation scheme based on the aided CS [21] is used to reconstruct IN. In order to identify the prior support set of IN, a new threshold \(k, l\) is proposed, where \(k = \frac{\sigma_y^2}{\sigma_z^2 + \sigma_w^2}\), \(\sigma_y^2\) is the power of the transmitted signal, \(\sigma_z^2, \sigma_w^2\) is the power of the background noise, \(p\) is the estimated probability of IN, \(N\) is the size of IFFT. With these parameters, the priori information of IN partial support can be identified as

\[
\Omega^{(0)} = \{n | |r_n|^2 > k, n = 0, 1, \ldots, N - 1\}
\]

(26)

The partial support will help improve the performance of the CS algorithm for IN recovery, especially in bad conditions where the INR is relatively low or the sparsity level is large.

### 4.4 Adjustment of NNC and LI

In practical power line communication systems, the sparsity of IN changes considerably over time, there are more IN disturbances in some hours of the day than the others. Therefore, a flexible IN mitigation method is proposed to suppress IN by changing NNC and LI according to the current characteristic parameters of IN. When the disturbance ratio of IN is high, we need more null subcarriers and longer LI for CS to estimate IN. On the other hand, when disturbance ratio is low, the IN can be estimated by less null subcarriers and shorter LI, which saves the bandwidth of the system and improve the overall throughput. Figure 5 shows the BER performance of the proposed compress sensing algorithm affected by varied LI and NNC. The modulation mode is QPSK, two IN samples measured in Sect. 2 were used, one samples is the weak IN \((p = 0.01 \text{ and } \mu = 10)\), and the other is heavy IN \((p = 0.20 \text{ and } \mu = 1000)\).

In Fig. 5(a), when weak burst IN occurred, there is a general trend of the BER performance increasing with the growth of NNC and LI. This trend is more pronounced as NNC goes below 130, when NNC is greater than 130 and LI greater than 10, the BER performance becomes very flat. This observation can be explained that the higher value of LI, the higher dispersion capability of interleaver becomes. In addition, higher NNC results in improvement of performance for reconstructing IN. On the other hand, when heavy burst IN occurred, small NNC and LI cannot work anymore, so the NNC and LI should be increased to maintain low
BER, the appropriate NNC and LI should be selected as 170 and 20 respectively. In practical communication system, the most effective method is to change LI and NNC adaptively according to the actual noise conditions.

5. System Simulation

In our simulations, the DFT size N is 512, the number of data sub-carrier is 128, the total NNC is 384, and the CP length is 32. To analyze and simulate the performance result of the proposed algorithm, two types of IN with different \( p \) and \( \mu \) are used in simulation, both of which are generated by opening fluorescent lamp and electric oven. Due to the focus of the paper is IN mitigation, a frequency-flat channel response is assumed and the impulse response of the channel is known in advance for all subcarriers. In the following section, we first designed a time-varying noise model based on the measured indoor IN, then the performance of proposed algorithm is compared with other IN mitigation methods based on CS, finally, the proposed algorithm is compared with nonlinear noise suppression methods.

5.1 Time-Varying Burst IN

In practical power line communication system, due to the different working conditions of electrical appliances, the power line noise shows different characteristics in different time periods. In this paper, we consider burst IN changes from one state to another. In simulation of 5.2 and 5.3, the simulation duration is divided into three stages, each of which consists of different interference rate \( p \). As shown in Fig. 6, a weak burst IN with parameters \( p = 0.01, \mu = 10 \) is used for the first stage of the simulation time, in the second stage, the noise is heavy burst IN, its characteristic parameters are \( p = 0.25, \mu = 1000 \), and the third stage returns to the weak burst IN state again. Therefore, the burst IN shows time-varying noise characteristics. In addition, the duration of each stage is determined by the selected LI in simulation.

5.2 Performance Comparison of IN Mitigation Algorithms Based on CS

Figure 7 shows the BER performance of the proposed IN mitigation algorithm compared with several other CS algorithms. The blue triangle line represents the BER performance of the proposed IN mitigation algorithm which selects NNC and LI according to the condition of IN adaptively. When weak burst IN occurred, NNC and LI are selected as 130 and 10 respectively. On the other hand, NNC=170 and LI=20 are selected when heavy burst IN occurred. Due to the length of the interleaver, the average NNC is 130 and the average LI is 12 for the proposed IN mitigation algorithm. In addition, the red circle line represents the CS algorithm that use fixed NNC (138) and adaptive LI(average LI=12), the black square line represents the CS algorithm that use fixed LI(12) and adaptive NNC(average NNC=138), the green asterisk line represents the CS algorithm that use fixed LI(12) and fixed NNC(138). It is clearly visible that the proposed algorithm is superior to other algorithms either NNC is fixed or LI is fixed. Note that when NNC and LI are fixed, as shown in green asterisk line, the performance of the CS algorithm is almost the worst. This can be explained that fixed NNC and LI cannot disperse and reconstruct burst IN well under time-varying noise conditions. Furthermore, we use scenarios with ‘No IN’ and ‘No interleaver’ to represent the two other possibilities for the purpose of comparison. It is interesting to note that ‘No
interleaver’ made the worst BER performance which is as poor as IN-mitigation algorithm is not applied. It can be explained that when interleaver is not used, the received signal is not sparse enough for CS algorithm to reconstruct the IN, so it is important to interleave the burst IN before it is processed by CS algorithms and select the NNC and LI adaptively according to the practical situation.

5.3 Performance Comparison between Different IN Mitigation Methods

In this section, we give the results obtained by comparing the proposed algorithm with conventional clipping, blanking and blanking-clipping algorithms. The BER performance of the proposed algorithm, blanking, clipping and combined blanking-clipping algorithms are depicted in Fig. 8. It is clearly seen that the proposed algorithm exceeds other nonlinear algorithms when $E_b/N_0$ is bigger than 2dB. In addition, when increase NNC and LI, the performance of the proposed algorithm is gradually improved. For example, when $E_b/N_0$ is fixed at 6 dB, the proposed algorithm (NNC=140, LI=12 ), (NNC=300, LI=20) and (NNC=380,LI=25) results in BER of $5.9 \times 10^{-4}$, $5.0 \times 10^{-5}$, and $8.2 \times 10^{-6}$ respectively. The gaps of BER between proposed algorithm and other IN mitigation algorithms are significantly enhanced with the increasing of $E_b/N_0$. This observation can be explained that the received signal is distorted when use conventional nonlinear IN mitigation algorithms. To the contrary, when use the proposed algorithm, IN is reconstructed accurately by using large NNC and can be well reduced by subtracting it from the received data. For the sake of comparison, the output BER of the typical OFDM receiver which named ‘no IN’ is also included in this picture, it represents the system contaminated by WGN only. It is evident that the BER performance of the proposed algorithm is very close to the ‘no IN’ situation when use large NNC and LI.

6. Conclusions

IN can cause serious problems in OFDM-based PLC systems and has become one of the major challenges in power line communications. In this work, we measured the indoor burst IN and proposed an adaptive IN mitigation algorithm. First, we disperse the long burst IN by using interleaver to make the IN sparse, then moment estimation method is used to estimate the characteristic parameter of IN, next, the IN is reconstructed by CS technique based on the estimated parameters, finally, the IN is subtracted from the received signal. The performance of the IN-mitigation algorithm can be adjusted by changing NNC and LI adaptively according to the noise conditions. Simulation results show that the proposed algorithm is superior to any other CS based algorithms that use fixed NNC and LI. Extensive numerical simulations show that the proposed algorithm provides drastic BER performance gains against well know nonlinear IN mitigation methods in different IN environments.

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