Pulse interference identification and suppression for OFDM signal

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Abstract. The new generation smart meter is the core node of information acquisition and flows in the power Internet of Things (IoT). Because it is powered by the low-voltage power line, various short-time pulse interference signals in the line can be easily coupled to the received signal of the communication module embedded in the meter, resulting in the degradation of communication performance. In view of this situation, an identification-suppression algorithm of the short-time pulse-interference signal is proposed. The core idea is to comprehensively judge the existence of the interference signal and its specific position in the time domain based on the energy ratio of adjacent OFDM symbols and the change of mean square error value between frequency domain amplitude signals. Based on this, an interference energy elimination scheme with an adaptive threshold is realized. Theoretical analysis and simulation results show that the scheme has low computational complexity, high accuracy of pulse interference identification and position judgment, and can effectively reduce the energy of pulse interference signal, and thus improving the decoding performance of OFDM while it receives signals.

1. Introduction

Smart meter, as the basic and key asset of smart grid and Ubiquitous Electric Internet of Things (UEIOT), has functioned as a comprehensive sensor in low-voltage power grid from the initial device to count the amount of the power consumption. It is not only the source to obtain the users’ power consumption information, but an important source to receive the operation data in the power grid [1-2]. The electricity meter is powered by the power lines, which connect with a large number of various types of power loads. The startup and operation of those power loads will cause pulse interference signals in a short time arising from the lines, and will decrease the decoding performance of the electricity meter, due to the presence of residual interfere energy coupled into the received signals of the communication module embedded in the electricity meter, despite the preprocessing of those pulse interferences.

Orthogonal frequency-division multiplexing (OFDM) technology [3] has been the standard for numerous types of communications [4-5], thanks to its advantages in terms of spectrum efficiency and channel equalization complexity, including various types of communication standards that have been widely used in electricity meters [6-8]. Pulse interference has the characteristics of random burst, short duration and high interference amplitude [9-11], and its interference energy in the time domain will diffuse in the time-frequency conversion procedure when OFDM receives signals, which leads to the disturbance exerted to a large amount of frequency-domain signals, resulting in the dramatically decreasing decoding performance for the received signals.
Since the pulse interference will partially cause the abnormal amplitude of the received signals, the commonly used method to eliminate the noise is to detect the amplitude of the input signal and then to set the signal over the prescribed threshold to zero, in order to suppress the interference signal energy. On the other hand, in the OFDM communication system, the characteristics of multi-carrier signals make its emission signal encounter Peak-to-Average Power Ratio (PAPR) in the time domain. Besides, the signal transmission is also influenced by the channel time-varying, multi-path transmission and channel noise, resulting in sharp fluctuations of the amplitude envelope of received signals that are not affected by pulse interference, thus, the threshold with constant value cannot be set in turn. For the OFDM system with Phase-Shift Keying (PSK) modulation, this paper introduces a short-time pulse interference signal recognition and energy suppression algorithm in the procedure of receiving signals, for which the focus is to calculate the energy ratio of the adjacent OFDM symbols and the mean squared error between amplitude signals in the frequency domain. According to the changes of the previous values, it is to make sure that whether there is a short-time pulse interference signal in the received signal or not, and to ensure the concrete position of the interference signal in the time domain, in order to realize the suppression of pulse interference energy based on an adaptive dynamic soft threshold. The presented theoretical analysis and simulation results show that the proposed method has low computational complexity, high accuracy of pulse interference identification and position judgment, which can effectively suppress the energy of pulse interference signal and improve the decoding performance of receiving signal.

2. Identification and Suppression Algorithm of Short-Time Pulse Interference Signal

2.1 System Interference Model

Assuming that the communication module in the electricity meter adopts OFDM technology, with N subcarriers and PSK modulation technique, the calculation procedure to transform the frequency domain signal into the time domain one by the sender, i.e. inverse discrete Fourier transform (IDFT), is expressed as below.

\[ x(k) = IDFT(X) = \sum_{n=0}^{N-1} X(n) e^{\frac{j2\pi kn}{N}}, \quad k = 0, \ldots, N - 1 \]  

(1)

where \( X = [X(0), X(1), \ldots, X(N - 1)] \) represents frequency domain signal, and \( x = [x(0), x(1), \ldots, x(N - 1)] \) stands for the corresponding time-domain signal, which is rewritten as \( \tilde{x} = (x_{N-M}, \ldots, x_{N-1}, x_0, x_1, \ldots, x_{N-1}) \) after inserting the cyclic prefix signal with length M.

On the other hand, the received signal can be expressed as

\[ r = H \tilde{x} + W + I \]  

(2)

where \( H \) stands for channel matrix in the transmission, and \( W \) stands for the channel white noise that can meet the characteristics of complex Gaussian distribution, and \( I \) stands for the short-time pulse interfere signal of the received signals by the external influence factors.

After removing the cyclic prefix at receiving end, the frequency domain signal can be obtained by means of discrete Fourier transform (DFT). According to the principle of OFDM communication, the frequency domain signal can be expressed as:

\[ R = \Lambda X + F_N I + F_N W \]  

(3)

where \( \Lambda \) is a diagonal matrix, and \( F_N \) is an N-order Fourier transform matrix.

It is seen from Eq. (3) that the signal corresponding to the channel white noise after DFT can still meet the characteristics of the white noise distribution. Moreover, for the short-time pulse signal interference, only a small proportion of elements in the time domain have large absolute values with the remaining equal to 0, and the interference energy will be extended to all the frequency domain.
signals of the influenced OFDM symbols after DFT. This phenomenon will reduce the signal-to-noise ratio for a higher proportion of elements in the corresponding coding block, which will sharply decrease the signal decoding performance.

Interference is a perpetual problem in the field of communications. So far, there are many mature technical solutions for the identification and suppression of short-time pulse interference. However, in OFDM systems, these traditional solutions face the following difficulties:

1. The multi-carrier characteristics of OFDM signal leads to high PAPR;
2. Channel multipath transmission, channel noise and other related factors will cause more serious envelope fluctuation of the received signal;
3. Communication channels generally have a high time variance, and the generation and numerical distribution of short-time pulse signals have heavy randomness;
4. In the transmission procedure, the communication signal may have huge fading changes due to the presence of obstructions and other factors, resulting in significant energy fluctuation of OFDM symbols at different positions even without pulse interference.

The previous factors may cause large fluctuations in the envelope and energy distribution of the received signal by OFDM, introducing great trouble in the determination of pulse interference, interference location and denoising threshold setting, which makes some traditional interference identification and suppression algorithms not applicable to the technical field of communications.

2.2 Interference Identification and Localization Algorithm

For the OFDM communication system with phase modulation (PSK) and N subcarriers, if there is short-time pulse interference in its communication environment, the following interference identification scheme will be added to its signal processing, which was shown below:

Step 1: If the Cyclic Redundancy Check (CRC) detection result of a received packet signal after decoding is wrong, it is considered that it may be subject to short-time pulse interference, and the identification of short-time pulse interference is started for the received signal;

Step 2: Assuming that the received signal contains K OFDM symbols, the received signal in the time domain after removing the cyclic prefix will be noted as:

\[
y = (y_{1,0}, y_{1,N-1}, y_{2,0}, \ldots, y_{2,N-1}, \ldots, y_{K,0}, \ldots, y_{K,N-1})
\]

where \(1^\circ\) symbol \(2^\circ\) symbol \(K^\circ\) symbol

Step 3: Applying discrete Fourier transform (DFT) to these time-domain symbols sequentially, the frequency domain signal is obtained as

\[
Y = (Y_{1,0}, \ldots, Y_{1,N-1}, Y_{2,0}, \ldots, Y_{2,N-1}, \ldots, Y_{K,0}, \ldots, Y_{K,N-1})
\]

where \(1^\circ\) symbol \(2^\circ\) symbol \(K^\circ\) symbol

Step 4: Calculating the energy of the K frequency-domain symbols in Eq. (5) and note as

\[
P = [P_1, P_2, \ldots, P_K],
\]

where

\[
P_k = \sum_{n=0}^{N-1} |Y_{k,n}|^2
\]

Step 5: Calculating the amplitude signal of the K frequency-domain symbols in Eq. (5) and the mean squared errors (MSE) between the adjacent amplitude signals, expressing as

\[
MSE_k = \frac{1}{N} \sum_{n=0}^{N-1} (|Y_{k+1,n}|-|Y_{k,n}|)^2, k = 1, \ldots, K-1
\]

Step 6: Based on Eq. (6), the energy ratio between the adjacent symbols can be calculated, namely,
\[ R_k = \frac{P_{k+1}}{P_k}, k = 1, ..., K - 1 \] \tag{8}

It is noteworthy that since the PSK modulation mode with constant amplitude is adopted, the OFMD signal has equal amplitude in the frequency domain. The parameter $MSE_k$ in Eq. (7) represents the similarity between the frequency domain amplitude signals of the $k+1$th and $k$th OFDM symbols, and a larger value means weaker similarity. On the other hand, the parameter $R_k$ in Eq. (8) represents the similarity between the energy of the $k+1$th and $k$th OFDM symbols, and the similarity is higher if the value is close to 1. Considering that the two adjacent OFDM signals with convergent channel fading, the following conclusions listed in Table 1 are drawn with respect to the four cases that the two adjacent OFDM symbols encounter short-time pulse interference or not.

| Parameters with Different Interferes | (none, none) | (with, none) | (none, with) | (with, with) |
|-------------------------------------|-------------|-------------|-------------|-------------|
| $MSE_k$                             | \approx 0   | Relatively large | Relatively large | Relatively large |
| $R_k$                               | \approx 1   | \gg 1       | \ll 1       | \approx 1   |

Step 7: Sorting the frequency domain symbols in Eq. (5) in descending order according to the symbol energy size. Based on the sparse characteristics of the short-time pulse interference signal in the time domain, the symbols smaller than the middle default energy value are considered free of pulse interference;

Step 8: Based on these default symbols that are not interfered with by the pulse, it is to check whether there are symbols interfered by the short-time pulse signal among the remaining ones, for which the procedure is structured as follows:

8.1) Set threshold $C = 1.5 \times \min(MSE_1, MSE_2, ..., MSE_{K-1})$;

8.2) Assuming that the $k$th symbol is supposed to have not interfered, and the adjacent one on the left side (i.e., the $(k-1)$th symbol) has not been checked, the decision algorithm is depicted as

\[
D_{k-1} = \begin{cases} 
\text{without interference, if } R_k \geq 2/3, \text{ and } MSE_k \leq C \\
\text{with interference, else} 
\end{cases}
\tag{9}
\]

8.3) Assuming that the $k$th symbol is supposed to have not interfered, and the adjacent one on the right side (i.e., the $(k+1)$th symbol) has not been checked, the decision algorithm is depicted as:

\[
D_{k+1} = \begin{cases} 
\text{without interference, if } R_k \leq 1.5, \text{ and } MSE_k \leq C \\
\text{with interference, else} 
\end{cases}
\tag{10}
\]

8.4) By making use of the previous algorithms in subsection 8.2 or 8.3, it is to check whether the undecided symbols are disturbed or not sequentially, until the adjacent left and right symbols of all the symbols undisturbed are checked;

8.5) If there are still some symbols in undecided status after the completion of Step 8.4), they will behave like the followings:
In view of this, let suppose an undecided symbol with number a, and find a symbol with the closest time to itself that does not interfere. If the symbol is set as b, the decision algorithm of the symbol with number a is given by:

$$D_a = \begin{cases} 
\text{without interference, if } & \frac{P_a}{P_b} \leq 1.5, \text{and } \sum_{n=0}^{N-1} (|S_{a,n}| - |S_{b,n}|)^2 / N \leq C \\
\text{with interference, else} & 
\end{cases}$$

Upon the accomplishment of Steps 8.1-8.5, the judgment of all the symbols can be completed.

Considering the limited ability of error correction of channel coding, if a high proportion of the received signals encounter short-time pulse interference, the result of decoding error cannot be changed, even if the interference can be correctly identified. Therefore, the starting point of the design of this paper is that only a small percentage of the received signal may have interference signals in the signal, so the received signals are ranked by the energy magnitude, and by default half of the symbols with less energy are not interfered with; then, by utilizing the characteristics of the fading coefficients of adjacent symbols experiencing convergence channel. The mean square error and energy ratio of the nearest non-interference symbol and the symbol to be determined on the time axis. They are used to comprehensively evaluate whether the undecided symbol is affected by pulse interference, so as to ensure the short-term high-precision pulse interference identification and localization algorithm.

2.3 Adaptive Soft Threshold Based Interference Suppression Algorithm

After completing the identification and localization algorithm of the previous short-time pulse interference signal, if all symbols in the received signal are judged as non-interference symbols, it is considered that the signal-to-noise ratio of the signal is lower than the decoding threshold, leading to the failed decoding, which is reported to the high-level protocol for sequential processing. If it is determined that there are interfered symbols in the received signal, the following interference suppression will be applied to these symbols:

Step 1: Assuming that the $k_1$ th symbol is judged as undisturbed, and based on this symbol, it is to judge the $k_2$ th symbol as disturbed.

Step 2: According to the interference decision principle, it is known that $\frac{P_{k_2}}{P_{k_1}} > 1.5$, therefore, the energy of the pulse interference signal causes the abnormal energy value of the disturbed symbol. For the $k_2$ th time domain signal $y_{k_2} = [y_{k_2,0}, \ldots, y_{k_2,N-1}]$ in Eq.(4), it is to set an adaptive threshold $\Delta_{k_2}$ to carry out the following peak clipping processing on the signal amplitude, in order to eliminate the energy of pulse interference signal:
\[ y_{k_2,n} = \begin{cases} y_{c,n} \cdot \frac{|y_{c,n}|}{|y_{c,n}| + |y_{e,n}|} & \text{if } |y_{c,n}| \leq \Delta_k, \\ \Delta_k \cdot y_{c,n} / |y_{c,n}| & \text{if } |y_{c,n}| > \Delta_k, \end{cases} \quad n = 0, \ldots, N - 1 \]  \tag{12}

where the setting principle of the threshold \( \Delta_c \) is to make the energy of the \( k_2 \) th time domain symbol after peak clipping approximately equal to the energy of the \( k_1 \) th time domain symbol, namely, 

\[ \sum_{n=1}^{N} |s_{c,n}|^2 / P_{k_1} \approx 1 \]

Step 3: Replace the new time domain symbol obtained after peak clipping with the original symbol, and then re-perform the reception processing process for the new signal, including channel equalization (if any pilot signal falls in the interfered symbol) and channel decoding;

Step 4: Whether or not the new signal is successfully decoded, the results are reported to the top level for processing.

The energy suppression algorithm of short-time pulse interference signal is based on the energy level determined as non-interference symbol, and it is to carry out peak clipping for suppression processing on the disturbed time-domain symbol through the adaptive soft threshold method of Eq. (12), so that the processed signal energy tends to be consistent with the energy of non-interference symbol. This method can achieve a good balance between noise energy suppression and energy preservation of the original communication signal, in order to improve the signal-to-noise ratio of the frequency domain signal obtained by the discrete Fourier transform of the interfering time-domain symbols, which provides some help for the improvement of decoding performance.

2.4 Simulation Results

In this section, simulation tool by MATLAB is used to comprehensively verify the interference identification accuracy of the previous algorithm and the improvement of the decoding performance after noise suppression.

Here is an example of the QPSK modulation. The number of subcarriers is \( N = 512 \) and the cycle lasts with length of 1/4 symbol. The transmitted signal includes 32 OFDM symbols, and the transmitting channel is AWGN channel, of which the signal-to-noise ratio of the signal in the non-interference area is 0dB. Moreover, in the two interference areas, short-time pulse interference satisfying Gauss distribution occurs, and the signal-to-noise ratio of the interference area is equal to -6dB and -8dB, respectively. The amplitude of the received time domain signal, the location of the interference area and the soft threshold peak clipping are shown in the figure below:
Figure 2. Received signal and its peak clipping of threshold in the disturbed area

The MSE values between adjacent symbols of the previous 32 OFDM symbols are depicted in the following figure:

Figure 3. The MSE values between two adjacent OFDM symbols

The energy ratio between the adjacent symbols of the previous 32 OFDM symbols is shown in the figure below:
Figure 4. The energy ratio between the two adjacent OFDM symbols

It can be observed from Figs. 2 to 4 that the pulse interference signal will lead to the local extreme value of MSE and energy ratio between the adjacent OFDM symbols, which can provide a reliable reference for interference identification, positioning and threshold peak clipping. The interference identification algorithm based on MSE and energy ratio can be adaptive to different communication environments and ensure high-accuracy decision results. Moreover, the noise energy suppression based on adaptive soft threshold can effectively remove the interference energy in the pulse interference area, and it will not introduce negative impact on the signal in the non-interference area.

In order to verify the improvement of decoding performance after noise suppression, modulation coding schemes of BPSK +1/2 turbo and QPSK +1/2 were taken as examples. Assuming that the channel is AWGN signal, and 1/32 of former and 1/16 of the received signals in time domain are interfered by short-time pulses with an interference signal ratio 10dB, the two following figures show the varying curves of packet error rate of the signals without pulse interference signal, with pulse interference signal and with noise suppression, in terms of the different signal-to-noise ratios of the two previous different modulation coding schemes, respectively.

It can be seen from the simulation results in Fig. 5 that when BPSK +1/2 turbo scheme is adopted, although only 1/32 of the time domain signal is interfered by short-time pulses, the noise energy will be extended to more frequency domain signals without denoising, resulting in a heavy loss of decoding performance, where the decoding performance decreases by about 5 dB at 10-3 packet error rate. On the other hand, after introducing the denoising algorithm, the noise energy is significantly suppressed, and about 4.2 dB signal processing can be gained.

As can be seen from the simulation results in Fig. 6, when the QPSK +1/2 turbo scheme is adopted, due to that 1/16 time-domain signal are interfered by the short-time pulse interference, the proportion of frequency-domain signal affected by its energy exceeds the upper limit of error correction ability of signal channel coding. In light of this, even if the signal-to-noise ratio in the undisturbed area can increase continuously, it still cannot be decoded correctly, which means that the receiver will not be able to correctly receive the communication packet data. After introducing the noise energy suppression principle, all decoding errors can be avoided when the signal-to-noise ratio of the undisturbed area is high. Although the error rate remains at a high level, the receiver can receive the correct data packet again.
3. Conclusions
Taking the influence of short-time pulse interference signals onto the communication module embedded in the smart meter of the OFDM system into consideration, this paper presents a simple but efficient algorithm for noise interference identification, localization and suppression algorithm. The algorithm can handle the problem of pulse signal recognition caused by the fluctuating envelope of OFDM signals, and realize accurate judgment and accurate localization of interference. Its adaptive soft threshold principle can significantly suppress noise energy, thus, it can help to improve significant signal processing gain to the decoding process of the received signal affected by short-time pulse interference.

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