G3-PLC Physical Layer Signal Processing Based on Mixed Window Function

Feng Zhang, Shangjun Yang, Li Zhao and Feng Xiao

***Abstract*—**In the signal processing of G3-PLC physical layer, ROBO mechanism is often used to ensure reliability in strong noise interference. But for non-Gauss channels, ROBO processing has the limited ability to improve communication reliability. Aiming at the existing problem of ROBO, analyzing the noise spectrum in the power line, FIR digital filter is introduced into the physical layer of G3-PLC in this paper. FIR band-pass digital filter is used to remove the out of band noise, enhancing the effect of ROBO processing, thereby improving communication reliability. Through the analysis of the main lobe width and the stop band attenuation, the mixed window function with reasonable parameters is used in the design of the filter to improve the denoising performance of the filter. The reliability and efficiency of the algorithm are simulated by measurement power line noise. The results show that the FIR filtering algorithm based on mixed window function has the coding gain of 1 to 2dB.Combined with ROBO processing, the algorithm has a coding gain of about 7dB to 8dB.The FIR filtering of signal in physical layer based on mixed window function is an effective way to improve the reliability of G3-PLC communication under strong noise interference in practical applications.

***Keywords*—**power line communication, mixed window, finite impulse response digital filtering, reliability, reliable mechanism.

I. INTRODUCTION

G3-PLC is the global power line communication (PLC) protocol designed for smart grid communication. This standard was initiated by the French power grid transportation company (ERDF), jointly developed by Maxim and Sagem Communications. Because the environment of power line communication channel is complex, the noise is strong and diverse, how to ensure the reliability of communication is the core issue in the field of PLC.

The physical layer is the basic level of G3-PLC.In order to cope with the bad channel environment of power line communication,G3-PLCphysical layer uses orthogonal frequency division multiplexing(OFDM) as the core technology, and combines a variety of forward error correcting codes and complex interleaving techniques to provide the basis for reliable data transmission in [1]-[2]. In the latest G3-PLC physical layer standard, a reliable mechanism robust (ROBO) is introduced to ensure the reliability of the communication in the strong noise background. Related literature analysis shows that, for the Gaussian noise, the introduction of the ROBO mechanism brings about 3dB coding gain when the bit error rate (BER) is 1%. However, the effect of the ROBO mechanism on the measured power line noise is not obvious, and the repeated processing will reduce the communication efficiency in [3]-[4].

In view of the practical application of ROBO mechanism, based on the spectral analysis of power line noise in non-Gauss channel, the mixed window function is applied to the G3-PLC physical layer in this paper to form digital filtering algorithm suitable for G3-PLC physical layer signal processing. This filtering algorithm can remove the out of band noise as much as possible, so that the effect of ROBO treatment is better. The combination of digital filtering and ROBO processing in G3-PLC physical layer signal processing has a significant improvement on the BER performance, when the BER is 1% the coding gain can achieve 7dB to 8dB.

II. P3-PLC PHYSICAL LAYER MODEL AND SIGNAL SPECTRUM ANALYSIS

A. Analysis of physical layer model of G3-PLC

The power line communication channel is characterized by strong time-varying, strong harmonic interference, strong noise and large signal attenuation. Due to the complexity of power line communication channel, the G3-PLC physical layer takes the high reliability OFDM technology as the core at present, and combines the efficient channel coding technology and powerful error correction mechanism. The physical layer model is shown in Fig.1.

The upper part of Fig.1 is the sending module. The data is scrambled and then encoded by Reed-Solomon and convolution codes. Reed - Solomon coding with convolution coding has a good forward error correction function, which can eliminate the error in the transmission process. The encoded data are interleaved to make the bit error random, which is convenient for error correction. After interleaving, the data is modulated (G3-PLC supports DBPSK and DQPSK two ways

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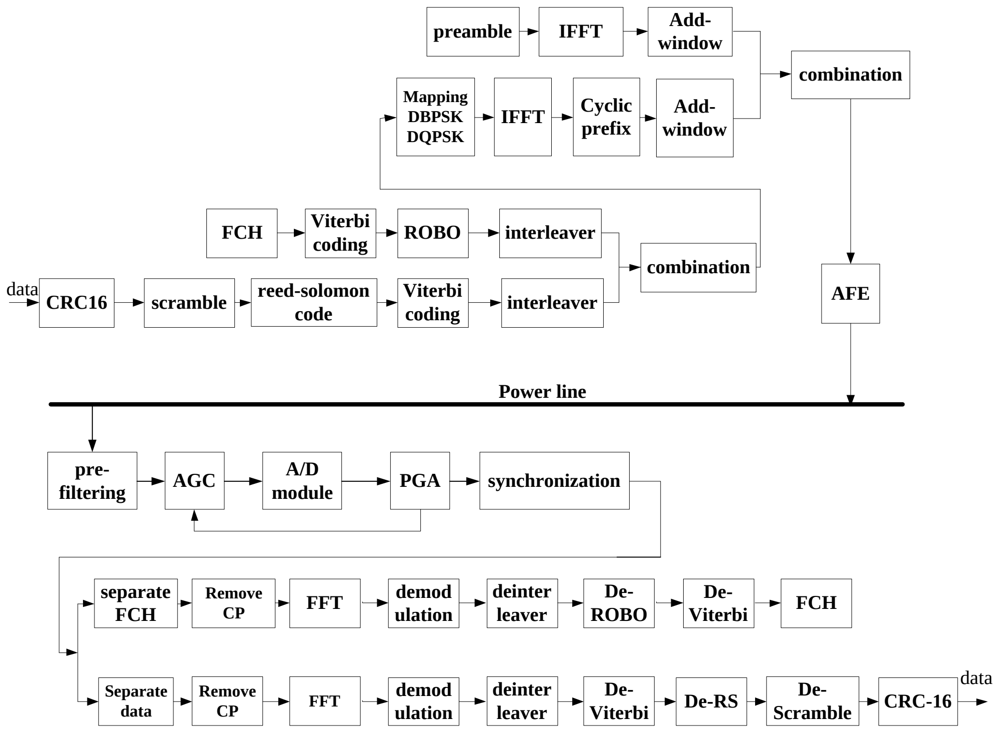

Fig. 1.G3-PLC physical layer model

for modulation), and then IFFT transform. Thus, the original OFDM signal is formed. In order to eliminate inter symbol interference and inter channel interference, cyclic prefix and windowing are needed for OFDM signal. Finally, the signal is amplified and coupled to the power line through the analog front end. The lower part of Fig.1 is the receiving module, which is the inverse operation of the sending module according to [5]. The received signal by the power line is pre-filtered and automatic gain amplified, and then demodulated, and finally the physical layer signal is reduced to the original data according to [6]. The ROBO in Fig.1 is an optional mode. In G3-PLC, the ROBO mechanism copies the data 3 times to guarantee the reliability of communication by sending the same data 4 times according to [7]-[9]. ROBO can be regarded as the reliability processing in time domain, so the effect is not ideal when the noise is non-Gauss noise. At the same time, due to multiple repeated transmissions, the effective communication rate in ROBO mode will be significantly reduced, according to [10]-[11].

B. G3-PLC physical layer signal spectrum analysis

Because the ROBO mechanism of G3-PLC has limited effect in practical application, the research of this paper is based on the measured power line noise. The ideal physical layer signal is added with the measured power line noise, and then the power spectral density of the signal is calculated by periodogram algorithm. The corresponding calculation formula is as (1):

$$P_{xx}(k)=\frac{|X(k)|^2}{N} \quad (1)$$

For equation (1), $X(k)$ is the N points discrete Fourier transform of the signal to be analyzed. The formula for calculating $X(k)$ is as (2):

$$X(k)=\sum_{n=0}^{N-1}x(n)e^{-j\frac{2\pi}{N}kn} \quad (2)$$

The power spectral density of the signal before and after being noised is calculated and plotted as shown in Fig.2. As can be seen from Fig.2 (a), the frequency range of the physical layer signal that is not contaminated by noise is 35.9 kHz to 90.6 kHz, the amplitude is about 30dBuV. The magnitude of the signal component outside this band is small, far below 30dBuV.As can be seen from Fig.2(b), the physical layer signal contaminated by the measured power line noise has a strong noise component outside the 35.9kHz to 90.6kHz band. At the same time, the power spectral density distribution of the noise is not equal, and the amplitude of the low-frequency part is even more than the amplitude of the useful signal. Out of band noise component is one of the main factors that affect the performance of BER, and it will also restrict the performance of ROBO processing. Because of the obvious difference between the noise frequency range and the useful signal frequency range, we can design a classical digital band-pass filter to remove the out of band noise component. On this basis, the influence of the out of band noise on communication performance can be reduced, and the reliability of the communication can be enhanced.

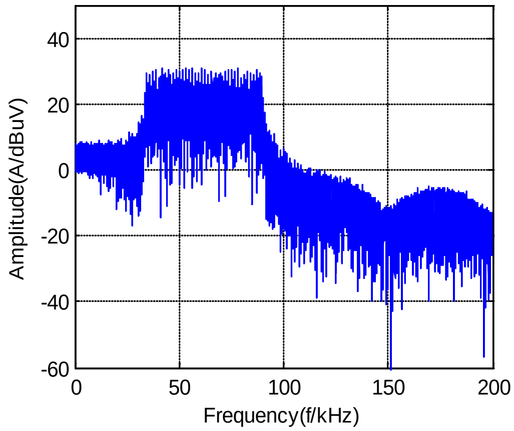

Fig. 2(a). Power spectral density for the signal without noise

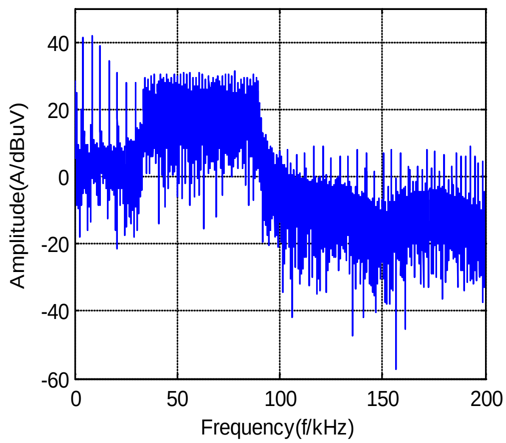

Fig. 2(b). Power spectral density for the signal with noise

III. Design and Implementation of Physical Layer Signal Filtering Algorithm

A. *Design of digital filter algorithm for physical layer signal*

Considering that the OFDM modulation technology is more sensitive to the phase of the signal, if the digital filter is a nonlinear phase frequency characteristic, it will affect the orthogonality of the OFDM, so it is necessary to avoid the distortion of the phase. The finite impulse response (FIR) digital filter with linear phase characteristics can avoid this problem. The cutoff frequencies of the upper and lower bands are $f_1 = 35\text{kHz}$ and $f_2 = 91\text{kHz}$, respectively. Then the unit sample sequence response of the filter can be calculated by (3):

$$h(n) = \frac{\sin[\omega_2(n-m)] - \sin[\omega_1(n-m)]}{\pi(n-m)} \qquad (3)$$

In (3), ω_1 and ω_2 are respectively the upper band cutoff (corner) frequency and the lower band cutoff (corner) frequency of the band -pass digital filter. The formulas used to calculate ω_1 and ω_2 are as (4) and (5):

$$\omega_1 = 2\pi \times f_1 \times T \qquad (4)$$

$$\omega_2 = 2\pi \times f_2 \times T \qquad (5)$$

Where T is signal sampling period. The $w(n)$ in (3) is a window function. It is related with the noise filtering effect, so it can be a rectangular window, Hanning window, Blackman window or Kaiser Window etc. physical layer signal processing The width of the window, that is, the order of the filter only affects the range of the transition band. In order to reduce the amount of calculation, the order does not need to be calculated, can be set directly, generally in the dozens of orders (odd numbers). m is the displacement coefficient, which is determined according to the order of the filter:

$$m = \frac{N-1}{2} \qquad (6)$$

B. *Application of mixed window function in filtering algorithm*

For the physical layer signal processing, it is necessary to remove the out of band noise as much as possible, and to ensure that the useful signal has no obvious attenuation. Considering the processing speed, the order of the filter needs to be as low as possible. These require that the window function has strong side-lobe attenuation when its main-lobe width is a certain value. In order to achieve this requirement, the mixed window function is introduced into the design of the filter. The definition of the mixed window function is shown in (7):

$$w(n) = \begin{cases} \alpha - \beta\cos\left(\frac{2\pi n}{N-1}\right) + \gamma\sin\left(\frac{\pi n}{N-1}\right) & 0 \le n \le \frac{N-1}{2} \\ 0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right) & \frac{N+1}{2} \le n \le N-1 \end{cases} \qquad (7)$$

For the equation (7), the first half of the window function is the superposition of the rectangular window, sine window, and cosine window, and the second part of the window is the latter half part of the standard Hamming window. N is the length of the window function, only affect the transition band width of the filter. α , β and γ are adjustable coefficients, which will affect the main-lobe width and side-lobe attenuation of the window function, which determines the effect of noise filtering. These three parameters can be adjusted according to the experiments in the practical application, but need to meet:

$$\alpha + \beta + \gamma = 1 \qquad (8)$$

For $N = 31$, $\alpha = 0.42$, $\beta = 0.4$, $\gamma = 0.18$, the spectrum of mixed window and Hamming window is calculated and drawn as shown in Fig.3.

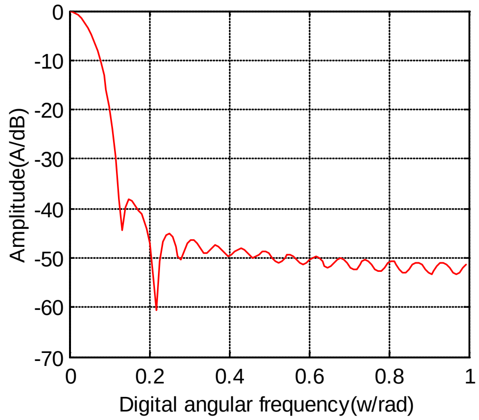

Fig. 3(a). Amplitude spectrum for mixed window

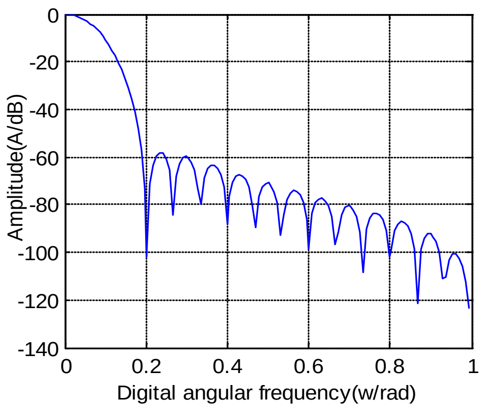

Fig. 3(b). Amplitude spectrum for Hamming window

It can be seen from Fig.3, in the same length N , the main-lobe width of the mixed window function and Hamming window function are the same, but the side-lobe attenuation of mixed window function is obviously stronger than that of Hamming window function. Because the side-lobe attenuation of the window function determines the stop-band attenuation and pass-band error of the filter, the filtering effect and error performance of the FIR digital filter designed with mixed window function will be better when the window length is certain. Therefore, the design of FIR digital filter in this paper is based on the mixed window function. That is using the mixed window function defined by (7) to replace the $w(n)$ in (3).The parameters α , β and γ in (7) can be adjusted according to the communication reliability requirements.

C. *The application of filter algorithm and its efficiency analysis*

The application of the designed digital filter in the signal processing of G3-PLC physical layer is essentially convolution calculation. That is, if $x(n)$ is a physical layer signal with noise, then the filtered signal $y(n)$ will be:

$$y(n) = x(n) * h(n) \tag{9}$$

The convolution operation can be calculated by Fast Fourier Transform (FFT), and the efficiency is high. Considering the obvious difference between the order of the filter and the length of the frame of the physical layer signal, the convolution operation can also be done in the form of subsection to further improve the efficiency. Since the FPGA devices or high performance DSP devices have been widely used in the physical layer chip or module design, the calculation can be completed in a very short time. At the same time, convolution operation can also be realized by hardware multiplication unit or butterfly unit integrated in the chip. In other words, convolution operation cannot obviously affect the real-time performance of physical layer signal processing. Since the frequency range of the physical layer signal is relatively fixed, the unit sampling response sequence of the filter is fixed too. It can be calculated and stored in advance, and can be used directly when the filtering algorithm is realized. In other words, the design and calculation of the filter will not bring additional system load. All of these show that it is feasible to use the classical digital filter to denoise the physical layer signal.

IV. Simulation Experiment and Data Analysis

A. *Description of the simulation experiment*

The performance analysis of the algorithm is based on the standard simulation program of G3-PLC physical layer model. The designed digital filter is added to the output of the PGA module and the input of synchronization module in the receiving part of G3-PLC physical layer model. Then the signal is processed by digital filtering. The simulation experiment environment is Matlab2012a, and the related parameters are as follows: the sampling frequency is 400kHz; the transmitted data is 1912bits per frame; the data modulation mode is DQPSK; 1000 frames are transmitted at each SNR.

B. *Performance analysis of digital filtering algorithm*

The measured power line noise is added to the physical layer signal, the SNR is -19dB to -5dB and the interval of SNR is 1dB. The error rate performance curve of the simulation program is shown in Fig.4.

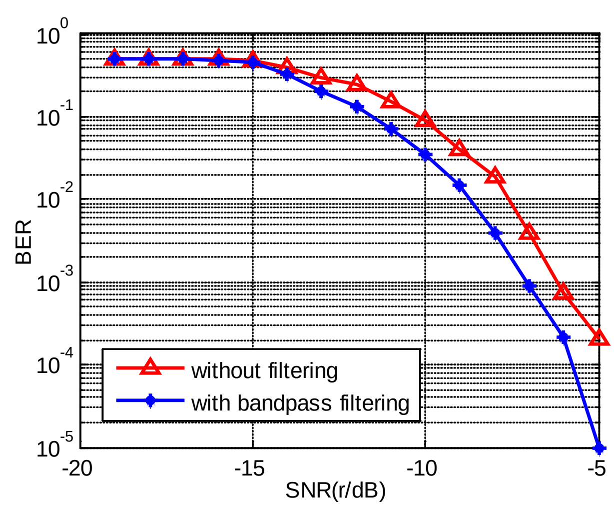

Fig. 4.BER performance curve (with the noise of power line's measurement)

As can be seen from Fig.4, for measured power line noise, when the SNR is higher than -16dB, the BER performance of the filtering algorithm is significantly better than that of the non-filtering algorithm. When the BER is 1%, the digital filtering algorithm itself has about 1.5dB coding gain. This result suggests that using the designed digital filtering algorithm for processing physical layer signal can significantly improve the reliability of communication and enhance the anti-interference ability.

Add white noise to the physical layer signal, the SNR is -5dB to 5dB, the interval is 1dB. The error rate performance curve of the simulation program is shown in Fig.5.

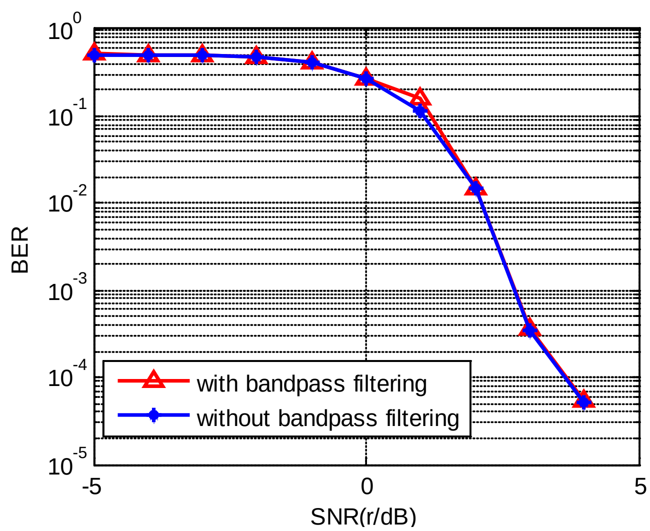

Fig. 5.BER performance curve (with the Gaussian noise)

As can be seen from Fig.5, for the Gauss noise, the two BER performance curve is basically coincident. The results show that although the proposed filtering algorithm cannot improve the reliability of the communication, but it will not have a negative impact on the reliability.

C. The Performance analysis of the combination of digital filtering and ROBO processing

The actual power line noise consists of both the Gaussian noise component and the non-Gaussian noise component. Thus, when the demand for communication speed is not high, the combination of digital filtering algorithm and time domain ROBO mechanism will have more effective noise suppression effect.

The running mode of the simulation program is set to ROBO mode, and the proposed filtering algorithm is combined. The resulting BER curve is show as Fig.6.

As can be seen from Fig.6, the combination of digital filtering and ROBO processing has a significant improvement on the BER performance of the system, and has a coding gain of 7dB to 8dB when the bit error rate is 1%.The results show that the digital filtering algorithm can better play the actual effect of the ROBO mechanism, and then improve the reliability of power line communication in the presence of large noise.

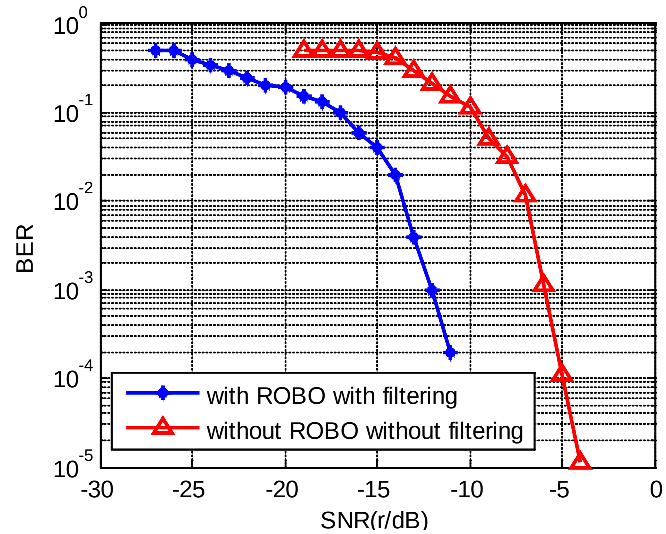

Fig. 6.BER performance curve (with ROBO and with filtering)

Based on the above analysis, it is a feasible and effective way to improve the communication reliability by introducing digital filtering algorithm to remove the noise in the G3-PLC physical layer model.

V. Conclusions

In this paper, the communication reliability of G3-PLC model is studied. In view of the fact that the ROBO mode is not effective in the actual power line communication channel and the communication efficiency is low, the digital filtering method for physical layer signal is proposed to improve the reliability of the communication. Based on the analysis of the power spectrum density of the G3-PLC physical layer signal, the FIR band pass digital filter is introduced into the physical layer signal processing. At the same time, based on the analysis and simulation of the relationship between the relevant parameters of the mixed window function and its frequency spectrum, the mixed window function with reasonable parameters is used to design the FIR filter to improve the filtering effect. Simulation experiment and data analysis show that:

(1) For the real power line noise environment, it is feasible to improve the communication reliability by means of classical digital filtering. Combined with the ROBO mechanism, the coding gain can be improved obviously, which is an effective way to improve the reliability of power line communication in the background of strong noise.

(2)The FIR digital band-pass digital filter can be used to filter the G3-PLC physical layer signal, and it can obtain better filtering effect on the basis of no obvious phase distortion. At the same time, FFT can also be used for the rapid realization of the filtering algorithm.

(3)Compared with the classical window function, the mixed window function can greatly improve the side lobe attenuation under the condition that the width of the main lobe does not change significantly. Using the mixed window function to design the digital filter for G3-PLC physical layer signal can obtain better filtering effect with lower order, which is helpful to reduce the computation amount of the digital filtering and improve the processing speed of signal processing.

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