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Research on Acoustic Transmission in the Logging While Drilling Based on Precoding NC-OFDM System

Si-Min Wu [1] , Xiang Ling [2] , Wei Zhang [3 +] and Yi-Bing Shi [4]

[1,2] School of Communication and Information, University of Electronic Science and Technology of China, Chengdu 611731, China

[3,4] School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China

Abstract. The non-continuous orthogonal frequency division multiplexing (NC-OFDM) acoustics transmission system based on drill strings channel can achieve high-speed transmission for the logging data from the borehole. However, there are a series of problems in the system, such as high peak to average power ratio (PAPR) in the transmitter, and the transmission performance degraded by spectral nulls. Aiming for the problems above, a BPSK based on precoder is proposed in this paper. By this method the BPSK modulated data is translated from ±1 to half of 0 and half of $\pm\sqrt{2}$. Then the PAPR is reduced and the robustness of spectral nulls is improved.

Keywords: logging while drilling, high-speed transmission, PAPR; NC-OFDM, precoding, spectral nulls.

1. Introduction

With the rapid development of stratigraphic exploration technology, Logging While Drilling(LWD) has gained more and more attention recently. Though the channel formed by drill pipes and joints becomes the emphasis for acoustic transmission, it still has disadvantages such as the multipath fading and the strong noise, which influence the transmission seriously. Therefore how to reduce PAPR and improve the robustness of the spectral nulls without increasing the complexity of the transmitter plays an important role in the transmission system. Though NC-OFDM has been widely used in cognitive radio systems and has same advantages with traditional OFDM, it still has some disadvantages [1-2]. For example, the receiver cannot recover part of the original data when some sub-channels are in deep fading. Also because of the linear superposition of multiple sub-waves at the transmitter, the transmitted signal has a high PAPR which lead the nonlinear distortion of the transmitted waveform. In this paper ,a method is proposed to reduce PAPR and improve the robustness of spectral nulls in NC-OFDM system. First, we analyzed the physical structure of the drill strings channel and modeled it. Second, we simulated the transmission performance and the amplitude frequency response of the channel with the same drill pipes and joints and the channel with different drill pipes and joints. Third, a precoding matrix based on Haar wavelet is propose. Finally, we simulated the channels with different equalization method to find out if the the precoding NC-OFDM system can reduce PAPR and improve the robustness of spectral nulls. And which equalization method has the best performance is gained as well.

2. LWD Acoustic Telemetry System

2.1. Acoustic transmission model

+ Corresponding author. Tel:13194869424; fax: 028-61830584.
E-mail address: weizhang@uestc.edu.cn.

The drill pipes and joints are connected throughout the borehole to provide a reliable channel for acoustic transmission, which can be expressed as:

$$Y_s = H(S + N_b + N_e) + N_s \tag{1}$$

where S denotes the transmitted signal in the frequency domain. H denotes the frequency response of the drill strings channel. Y_s denotes the received signal in the frequency domain. N_b, N_e, N_s denote the drill bit noise, the downhole environmental noise and the surface environmental noise.

2.2. Frequency response of drill string channel

Because of the discontinuity of the drill strings, when the acoustic wave arrives at a nonuniform cross section, part of acoustic waves are reflected, which leads to the multipath effect in acoustic transmission. The stress condition of a structural unit is shown in Fig.1.

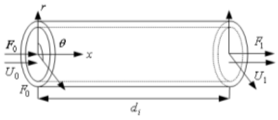

Fig. 1: structural unit mechanical model.

The solution of the longitudinal wave equation can be expressed as

$$U_x = (C_1 e^{jkx} + C_2 e^{-jkx})e^{-jwt} \tag{2}$$

where w is angular frequency, k is the number of waves, which is defined as $k = w/c$.The corresponding force can be calculated as

$$F_x = Es_i \frac{\partial U_x}{\partial x} \tag{3}$$

As for a structural unit, the force and displacement of both sides can be expressed as:

$$U_1 = \frac{1}{2}(e^{jkd_i} + e^{-jkd_i})U_0 - \frac{1}{2kEs_i}(e^{jkd_i} - e^{-jkd_i})F_0 \tag{4}$$

$$F_1 = -\frac{1}{2}kEs_i j(e^{jkd_i} - e^{-jkd_i})U_0 + \frac{1}{2}(e^{jkd_i} + e^{-jkd_i})F_0 \tag{5}$$

The displacement and force are continuous at the connections between the drill pipes and the joints, the relation can be expressed as

$$\begin{bmatrix} U_1 \\ F_1 \end{bmatrix}_i = \begin{bmatrix} U_0 \\ F_0 \end{bmatrix}_{i+1} \tag{6}$$

According to equation(4),(5),(6), we can obtain the relationship between the displacement and the force of a structure that cascaded by N structural units, which can be expressed as

$$\begin{bmatrix} U_1 \\ F_1 \end{bmatrix}_N = \mathrm{M}_N \cdots \mathrm{M}_2 \mathrm{M}_1 \begin{bmatrix} U_0 \\ F_0 \end{bmatrix}_1 \tag{7}$$

where M_n is the relation matrix of the displacement and force of the Nth unit.

Considering the abrasion in the machining and drilling, the variation of the pipes length can be regard as the Gaussian distribution (the rest of the size distribution can be discussed in the same way). Assuming that d_1 represents the mean value, and $d_1 \times 3\%$ represents the variance, the transmission characteristics of two channels formed by 20 drill pipes and 19 joints are simulated, respectively. In channel A, the size of the drill pipes and joints are the same, while in channel B, the size is in Gaussian distribution. The amplitude frequency response and the impulse response are shown in Fig.2.

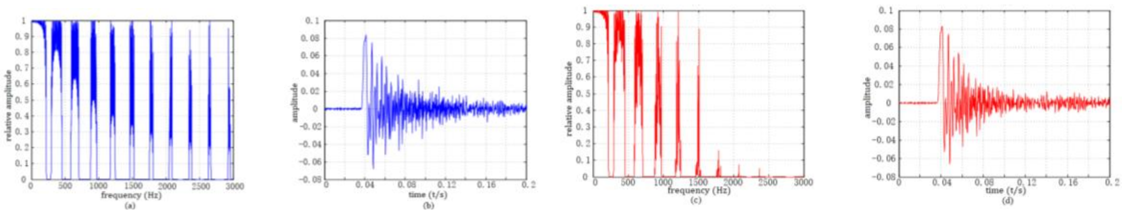

Fig. 2: Transmission performance of channel A and channel B, (a) amplitude frequency response of channel A; (b) impulse response of channel A; (c) amplitude frequency response of channel B; (d) impulse response of channel A.

As seen from Fig.2, the amplitude frequency response has comb filter characteristics. As the frequency increases, the width of pass-band is narrowed while the width of stop-band is widened, and the amplitude fluctuation in the pass-band increases. The channel formed of different length pipes is featured by serious amplitude-frequency attenuation and deep fading. The arrival times of the first path is related to the acoustic transmission rate and the length of the channel.

3. Transmission Design

3.1. Haar wavelet principle

As the most basic wavelet, Haar wavelet is a group of square-waves, whose amplitudes are ±1, whose time intervals are between 0 and 1 [3]. Assuming that there is a signal sequence $\mathrm{x} = \{x_1, x_2, x_3, x_4\}$, according to Haar wavelet scaling function and wavelet function, its average and detail can be calculated as

$$\begin{cases} a_{1,0} = (x_1 + x_2)/2 \\ d_{1,0} = (x_1 - x_2)/2 \end{cases} \tag{8}$$

$$\begin{cases} a_{1,1} = (x_3 + x_4)/2 \\ d_{1,1} = (x_3 - x_4)/2 \end{cases} \tag{9}$$

where a denotes the average or the value of low frequency, d denotes the details or the value of high frequency. Suppose that $\mathrm{a} = \{a_{1,0}, a_{1,1}\}$, $\mathrm{d} = \{d_{1,0}, d_{1,1}\}$, we can obtain

$$\begin{bmatrix} \mathrm{a}^T \\ \mathrm{d}^T \end{bmatrix} = \frac{1}{2}\mathrm{T}\mathrm{x}^T \tag{10}$$

The transformation matrix T can be expressed as

$$\mathrm{T} = \begin{bmatrix} 1 & 1 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \cdots & \vdots & \vdots \\ 0 & 0 & \cdots & \cdots & 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \cdots & \vdots & \vdots \\ 0 & 0 & \cdots & \cdots & 0 & 0 & 1 & -1 \end{bmatrix} \tag{11}$$

3.2. Precoding NC-OFDM system

The kth sub-channels transmission equation in the frequency domain can be represented as

$$Y(k) = H(k)X(k) + N(k) \tag{12}$$

where $X(k)$, $Y(k)$ are the transmitted and received data, respectively. $H(k)$ is the frequency response of the kth sub-channel. $N(k)$ is the white Gaussian noise component, and its power is σ^2. Assuming that the input data is $\mathrm{X} = [X(0), X(1), \cdots, X(N-1)]^T$, and X is modulated by the precoding matrix G. Then, we can obtain the encoded data $\hat{\mathrm{X}}$, which can be expressed as

$$\begin{pmatrix} \hat{X}(0) \\ \hat{X}(1) \\ \vdots \\ \hat{X}(N-1) \end{pmatrix} = \begin{pmatrix} X(0) \\ X(1) \\ \vdots \\ X(N-1) \end{pmatrix} \tag{13}$$

After coded by the matrix G, the data will not be transmitted independently through the sub-channels, therefore the diversity gain is obtained. In order to decrease the complexity of coding and decoding, G should be a sparse matrix.

Modulated by BPSK the data is formed of $\{1, -1\}$. When $\mathrm{G} = \mathrm{T}$, the range of $\hat{X}(k)$ is $\{\pm 2, 0\}$. Therefore, when $X(k) = 0$, $k = 0, 1, N/2-1$, we can obtain that $\hat{X}(k+N/2) = \pm 2$. Similarly, when $X(k) = \pm 2$, $k = 0, 1, N/2-1$ we can obtain that $\hat{X}(k+N/2) = 0$. After the precoding operation, half of the elements in $\hat{\mathrm{X}}$ are zeros, and the remainders are ± 2. To achieve constant bit transmission power, the precoding matrix G can be expressed as

$$\mathrm{G} = \frac{1}{\sqrt{2}}\mathrm{T} \tag{14}$$

3.3. PAPR reduction

After precoding operation, half of the data equals zero and the others equals $\pm\sqrt{2}$, therefore only half of the sub-channels have the transmitting power. Assuming that the power of all sub-channels reach the maximum, we can obtain that:

$$P_{\max,x} = N^2 \tag{15}$$

$$P_{\max,\hat{x}} = (\frac{N}{2}\times\sqrt{2})^2 = \frac{N^2}{2} \tag{16}$$

According to the equations (15) and (16), we find that the maximum power of the system is half less than the one without precoding, and the PAPR is 3dB reduced as well .

3.4. Transmission performance analysis

MMSE, ML and LS are commonly used equalization methods at the receiver.

The equalization operation of MMSE can be expressed as

$$\hat{X}(k) = H_{\text{MMSE}}(k)\hat{Y}(k) \quad (17), \text{ where } H_{\text{MMSE}}(k) = \frac{H(k)^*}{|H(k)|^2 + \rho^{-1}} \tag{18}$$

Then after decoding and demapping operations, the original data can be recovered.

We can detect in pairs when using ML equalization, and the equalization can be expressed as

$$\arg\min\left(\left\|\begin{bmatrix}\hat{Y}(k)\\ \hat{Y}(k+\frac{N}{2})\end{bmatrix} - \begin{bmatrix}H(k) & 0\\ 0 & H(k+\frac{N}{2})\end{bmatrix}\begin{bmatrix}\hat{X}(k)\\ \hat{X}(k+\frac{N}{2})\end{bmatrix}\right\|^2\right)(19) \quad \text{where} \quad \begin{bmatrix}\hat{X}(k)\\ \hat{X}(k+\frac{N}{2})\end{bmatrix} = \begin{bmatrix}\sqrt{2}\\ 0\end{bmatrix}, \begin{bmatrix}-\sqrt{2}\\ 0\end{bmatrix}, \begin{bmatrix}0\\ \sqrt{2}\end{bmatrix}, \begin{bmatrix}0\\ -\sqrt{2}\end{bmatrix} (20)$$

The corresponding data before precoding operation is:

$$\begin{bmatrix}X(2k)\\ X(2k-1)\end{bmatrix} = \begin{bmatrix}1\\ 1\end{bmatrix}, \begin{bmatrix}-1\\ -1\end{bmatrix}, \begin{bmatrix}1\\ -1\end{bmatrix}, \begin{bmatrix}-1\\ 1\end{bmatrix} \tag{21}$$

Then after demapping operation, the original data can be obtained.

Because the precoding matrix G is a unitary matrix, the system is a unitary matrix precoding system. Document [4] and [5] proved that the BER of MMSE and ML in a unitary matrix precoding system is lower than in the traditional ones, respectively. As for LS equalization, the BER varies from each sub-channel and is mainly related to the noise variance and SNR.

4. Verification and Analysis

In order to verify the effectiveness of the method, we select the channel A=[0.8, 0.6], which doesn't have spectral nulls but a few deep fading, to simulate and to compare with channel B which is shown in Fig.3. The transmission bands of channel B are [600, 707]Hz and [890, 969]Hz, and the numbers of the sub-channels are N_1=108 and N_2=108, respectively. To verify the robustness of this method when affected by the spectral nulls, the transmission bands of channel B are moved 10Hz close to the stop-bands, respectively.

4.1. Analysis of PAPR simulation results

After calculate the transmitted signals of the precoding NC-OFDM system and traditional NC-OFDM system, respectively, we obtain the comparison versus of the PAPR distribution probability shown in Fig. 3(a). From this figure, we find that the precoding system PARP is 2dB better than the traditional ones.

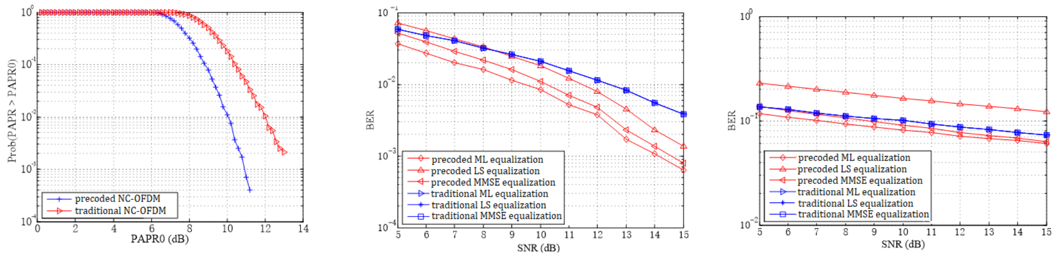

Fig. 3: (a) comparison of PAPR performance; (b) comparison of transmission performance under channel A; (c) comparison of transmission performance under channel B.

4.2. Analysis of transmission performance

ZF, MMSE and ML are adopted at the receiver and the corresponding BERs are analyzed, respectively. The transmission performance under channel A and channel B are shown in Fig.3(b) and Fig.3(c), respectively.

As shown in Fig.3(b), the precoding paired ML detection method has the lowest BER, closely followed by the MMSE detection method. However, when SNR is low, the BER of precoding LS detection is slightly larger than that without precoding. The transmission performance is poor without precoding, the BER curves of the three methods are coincident.

As shown in Fig.3(c), the BER in channel B is much lower than that in channel A. The precoding paired ML detection method is the most effective way, closely followed by MMSE method. Both of them can achieve lower BER compared with the traditional ones. However, the precoding LS method is the worst, which is not suitable for transmission.

4.3. The experiment

A channel formed of 6 drill pipes and 5 joints is made in laboratory. 590Hz and 600Hz are adopted as the carrier frequency of the up-conversion, and the BER at the receiver is shown in Fig.4(a) and Fig.4(b), respectively. When the up-conversion frequency is 590Hz, 20Hz spectral nulls are found in the transmission band.

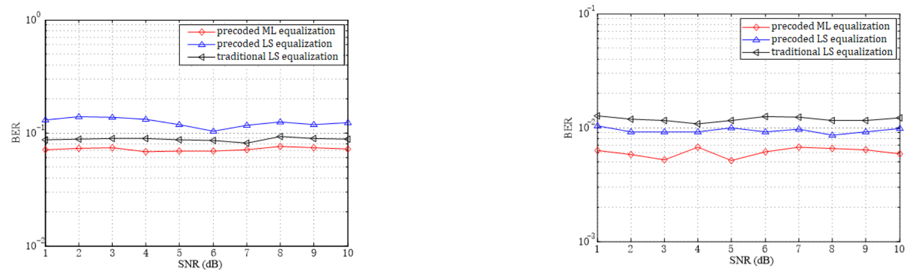

Fig. 4: (a) measured BER when up-conversion is 590 Hz; (b)measured BER when up-conversion is 600 Hz.

As shown in Fig.4, we obtain that the precoding paired ML detection method has a lower BER in the multipath fading channel. When there are lots of spectral nulls in the channel, the performance of precoding LS detection method is poor. When there is few deep fading in the channel, the precoding LS method has a lower BER compared with the one without precoding. The results of the circuit test are the same with the simulation ones.

5. Conclusion

A method of precoding NC-OFDM acoustic transmission based on cascaded drill strings channel is proposed in this paper, aiming for the low-speed in traditional LWD transmission. Simulation and test results show that after procoding the PAPR can be reduced 3dB at most and the BER is reduced compared with the traditional ones. And the precoding paired ML detection method has the lowest BER in the multipath fading channel and the low SNR channel. In our future research different baseband modulation scheme’s wavelet transmission will be involved.

6. Acknowledgements

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