APBT-Based Channel Estimation for OFDM System

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Abstract —Orthogonal Frequency Division Multiplexing (OFDM) has developed into a popular scheme for wideband digital communication, used in applications such as digital television and audio broadcasting, DSL Internet access, wireless networks, powerline networks, and 4G mobile communications. It plays an important role in the new generation of mobile communication. In OFDM system, channel estimation is a necessary technique for improving the system's accuracy at the receiving end. Therefore channel estimation based on pilot assistant has been a hot area of research for several years. Recently, the advantages of the Discrete Cosine Transform (DCT) based channel estimation have come to light. Compared to channel estimation based on Discrete Fourier Transform (DFT), DCT-based channel estimation could improve the performance of channel estimation, and it is also an efficient way to suppress the Gaussian white noise. A new transform called All Phase Biorthogonal Transform (APBT) was proposed in recent years, APBT has the similar energy compaction property of DCT. Therefore, a novel channel estimation based on APBT was proposed for QPSK and 16-QAM modulated signals in this paper. The proposed method can solve the low leakage problem which exists in DFT-based channel estimation and "error floor" which exists in DCT-based channel estimation. From experimental results, the APBT-based channel estimation provides improved performance in terms of Bit Error Rate (BER) and reduction in the Mean Square Error (MSE) compared to conventional channel estimation based on DFT and DCT.

Index Terms—Channel estimation, Orthogonal Frequency Division Multiplexing (OFDM), All Phase Biorthogonal Transform (APBT), Discrete Cosine Transform (DCT)

I. Introduction

High data rate information is required to meet the rapidly increasing demands for mobile communication. Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation technology that has been widely implemented in high data rate communication systems such as IEEE 802.11 WLAN [1], IEEE 802.16 WMAN, Digital Audio Broadcasting (DAB), Digital Video Broadcasting terrestrial (DVB-T), 3GPP LTE-A [2], 3GPP2 UMB and WiMAX [3]. OFDM technique has attracted much attention and found many applications due to its simple implementation, robustness against frequency-selective fading channels, and relative easiness to employ multiple-antenna transmission techniques. However, it still suffers from multipath frequency-selective fading. To remove the channel effect and achieve accurate data demodulation, precise channel estimation has to be performed.

In OFDM system, channel estimation is one of the key technologies. Channel estimation mainly has three kinds of methods [4]: pilot symbol assisted channel estimation, blind channel estimation and decision-directed channel estimation. The pilot symbol assisted channel estimation inserts the pilots into data symbols to estimate Channel Frequency Response (CFR). The blind channel estimation uses statistical characteristic of transmitted symbols to estimate the channel state information. The decision-directed channel estimation takes advantage of the channel response estimation value of the previous frame to estimate the channel response in current time. In practical application, the pilot symbol assisted channel estimation has become one of the efficient ways for channel estimation in the new generation of communication system. Compared with blind and decision-directed channel estimation, the pilot symbol assisted channel estimation is more simple and reliable [5].

The common pilot symbol assisted channel estimation algorithm, including Least Square (LS) estimation and Minimum Mean Square Estimation (MMSE) is a hot research field. LS estimation is one of the simplest estimators to find CFR [6], because LS channel estimation does not need the channel parameters in advance. Since it has no prior information of channel statistics, the Bit Error Rate (BER) performance of LS channel estimation is poor in fast fading environment [7]. BER of LS estimator can be improved by MMSE estimation by knowing some channel statistics in terms of autocorrelation of the channel in advance. The MMSE channel estimation [8] is optimal in Mean Square Error (MSE) sense. However, the statistical characteristics of a channel including autocorrelation matrix of CFR and Signal-to-Noise Ratio (SNR), must be obtained in advance. Although the performance of MMSE channel estimation is better than that of LS estimation, the computational complexity of MMSE channel estimation

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is too high to implement practically. A low complexity linear MMSE (LMMSE) method was proposed in [9]. However, the modified LMMSE method still has high computational complexity.

Currently, the popular channel estimation is based on Discrete Fourier Transform (DFT) or Discrete Cosine Transform (DCT) [10]-[12]. At first, the CFR could be got by applying LS criteria at pilot locations. Then the CFR of pilot sub-carriers is regarded as the input of DFT/DCT. After that, we pad zero at the end of "spectrum sequence" in the transform domain. Finally, the new "spectrum sequence" is transformed into frequency domain by Inverse Discrete Fourier Transform (IDFT) / Inverse Discrete Cosine Transform (IDCT) to get the whole CFR. In [13], DFT-based channel estimation was compared with DCT-based channel estimation. The channel estimation based on DFT method improves the performance by neglecting nonsignificant channel taps. However, in multipath channels, this will cause power leakage and result in an "error floor" [14]. In [15], the DCT-based channel estimation was proposed to solve the leakage problem. But the "error floor" still exists in DCT-based channel estimation.

In 2009, Hou *et al*. proposed the All Phase Biorthogonal Transform (APBT) [16], which is based on Walsh-Hadamard Transform (WHT), DCT, and IDCT. It is a new transform for image compression instead of DCT, which solves the problem of blocking artifacts in DCT-JPEG. Parallel APBT-JPEG based on GPU was proposed in [17]. In this paper, the APBT-based channel estimation was proposed. Because APBT transform has more concentrative energy property than that of DCT transform, the performance of proposed method is better than that of the conventional channel estimation based on DCT and DFT. In addition, APBT-based channel estimation can solve the "error floor" problem efficiently.

The rest of this paper is organized as follows. OFDM model, channel model, channel estimation based on LS are described in Section II. Section III starts with a brief review of APBT, property of APBT, and introduces the APBT based channel estimation. Experimental results of the proposed method are presented in Section IV. Conclusions and remarks on possible further work are given finally in Section V.

II. System Model

A. OFDM Model

A conventional OFDM system is illustrated in Fig. 1. The model mainly has three parts, the transmitter, channel and receiver [18]. At the transmitter side, OFDM transmitter maps the message bits into a sequence of QPSK or 16-QAM symbols which will be subsequently converted into N parallel streams by serial-to-parallel port. And the duration of the data is elongated by N times. When the parallel data streams are generated, each data stream would be carried at different center frequencies. And the modulated data $F(n)$ is converted into a time domain signal $f(k)$ by using IDFT. So the IDFT operation: $F(n) \xrightarrow{\mathrm{IDFT}_N} f(k)$ can be expressed as:

$$f(k) = \mathrm{IDFT}_N\left\{F(n)\right\} = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} F(n)\,\mathrm{e}^{\frac{\mathrm{j}2\pi kn}{N}} \tag{1}$$

where $n = 0,1,2,\cdots,N-1$, N is the length of DFT and $\mathrm{e}^{\frac{\mathrm{j}2\pi}{N}}$ is the twiddle factor of inverse fast Fourier transform (IFFT).

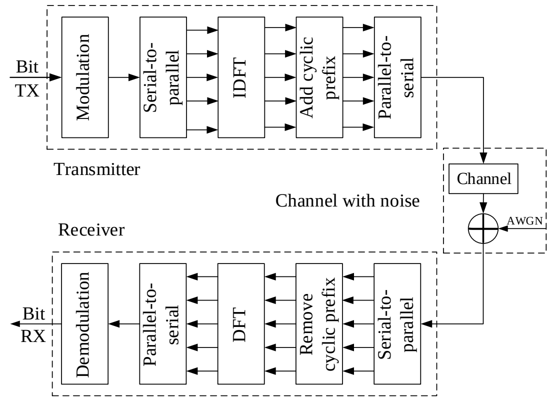


Fig. 1. OFDM model

Following the IDFT, the Cyclic Prefix (CP) or guard interval is inserted into the front of OFDM symbols at the transmitter. It is an efficient way to eliminate Inter-Symbol Interference (ISI) and inter-carrier interference (ICI). There are two ways to insert the guard interval in the OFDM system [19]. One is the cyclic extension of the OFDM symbol with CP or Cyclic Suffix (CS) as shown in Fig. 2, where the length of the guard interval is the sum of CP's length T_{CP} and CS's length T_{CS}; T_{sub} is the length of sub-carrier; the length of OFDM symbol is $T_{\mathrm{sym}} = T_{\mathrm{sub}} + T_{\mathrm{CP}} + T_{\mathrm{CS}}$. The other one is the zero padding (ZP) that pads the guard interval with zeros as shown in Fig. 3, where the length of the guard interval is the sum of zero length T_{G}; the length of OFDM symbol is $T_{\mathrm{sym}} = T_{\mathrm{sub}} + T_{\mathrm{G}}$. After the parallel data streams are converted into serial by parallel-to-serial port, the input data is transformed by the channel.

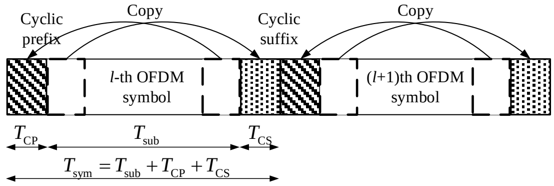


Fig. 2. OFDM symbol with both CP and CS

When the receiver gets the data streams, the received signals should be converted into digital forms. After that, receiver will remove the CP and rearrange it parallel. Following DFT, the data is transformed to frequency domain. Lastly, the binary information data is obtained after parallel-to-serial port and the demodulation with QPSK or 16-QAM decoder.

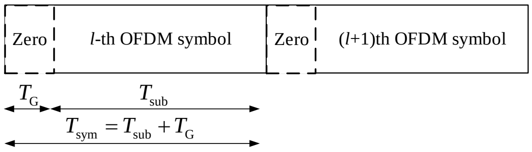


Fig. 3. OFDM symbol with ZP

B. Channel Model

When the guard interval is added, the data streams are transformed in the channel. At the receiver, because the effect of multipath fading and Additive White Gaussian Noise (AWGN), the time-varying channel impulse response can be characterized as:

$$h(t,\tau) = \sum_{l=0}^{L-1} \alpha_l(t) g(\tau - \tau_l) \tag{2}$$

where $\alpha_l(t)$ is the time-varying complex amplitude of l-th path; L is the number of paths; τ_l is the corresponding path delay, and $g(\tau)$ is the shaping pulse. After removing the cyclic prefix in the receiver, the received signal can be written as:

$$y(n) = \sum_{l=0}^{L-1} x(n-l) \otimes h(l) + w(n) \tag{3}$$

where $w(n)$ is the AWGN which is added in channel, and $h(l)$ is the channel impulse response.

C. LS Channel Estimation

LS estimation is the simplest channel estimation algorithm. The computational complexity of LS estimation is lower than other channel estimation methods. The channel frequency response of LS estimation can be represented by:

$$\boldsymbol{H}_{\mathrm{LS}} = \boldsymbol{X}^{-1}\boldsymbol{Y} \tag{4}$$

where $\boldsymbol{X}$ is the data which is sent in frequency domain. $\boldsymbol{Y}$ is the received signal. $\boldsymbol{H}_{\mathrm{LS}}$ is the response of the channel. The channel frequency response of LS estimation is obtained by minimizing the cost function as shown in Eq. (5):

$$\boldsymbol{H}_{\mathrm{LS}} = (\boldsymbol{Y} - \boldsymbol{XFh})^{\mathrm{H}}(\boldsymbol{Y} - \boldsymbol{XFh}) \tag{5}$$

where $(\cdot)^{\mathrm{H}}$ is the conjugate transpose of the matrix, and $\boldsymbol{h}$ is channel response. $\boldsymbol{F}$ is represented by:

$$\boldsymbol{F} = \begin{bmatrix} W_N^{00} & \cdots & W_N^{0(N-1)} \\ \vdots & \ddots & \vdots \\ W_N^{(N-1)0} & \cdots & W_N^{(N-1)(N-1)} \end{bmatrix} W_N^{nk} = \frac{1}{N}\mathrm{e}^{-\mathrm{j}2\pi(n/N)k} \tag{6}$$

Although LS estimation is easy to implement, LS estimation is susceptible to AWGN and ICI which exist in sub-carriers, so the accuracy of the estimation is limited. And the LS is applied in DFT domain and DCT domain to mitigate the contamination at the estimation process by exploiting DFT and DCT characteristics. The detail will be described in the next section.

III. Design of APBT-Based Channel Estimation for OFDM System

A. All Phase Biorthogonal Transform (APBT)

On the basis of all phase digital filtering, three kinds of all phase biorthogonal transforms based on the WHT, DCT, and IDCT were proposed and the matrices of APBT were deduced in [16]. Similar to DCT matrix, it can be used in image compression transforming the image from spatial domain to frequency domain.

Taking All Phase Discrete Cosine Biorthogonal Transform (APDCBT) for example, the process of two-dimensional APBT is introduced as follows. $\boldsymbol{x}$ is a signal sequence with N points, and $\boldsymbol{V}$ represents the APDCBT matrix with size of $N \times N$. After two-dimensional APDCBT transform, the transform coefficients sequence $\boldsymbol{y}$ can be denoted by

$$\boldsymbol{y} = \boldsymbol{Vx} \tag{7}$$

$$\boldsymbol{V}(m,n) = \begin{cases} \dfrac{N-m}{N^2},\ n=0,\ m=0,1,\cdots,N-1, \\ \dfrac{1}{N^2}\left[(N-m)\cos\dfrac{mn\pi}{N} - \csc\dfrac{n\pi}{N}\sin\dfrac{mn\pi}{N}\right] \\ n=1,2,\cdots,N-1,\ m=0,1,\cdots,N-1. \end{cases} \tag{8}$$

We use

$$\boldsymbol{x} = \boldsymbol{V}^{-1}\boldsymbol{y} \tag{9}$$

to reconstruct the signal, where $\boldsymbol{V}^{-1}$ is the inverse matrix of $\boldsymbol{V}$.

B. Property of APBT

DFT is widely used in signal processing, which is obtained by decomposing a sequence of values into components of different frequencies. This operation is useful in many fields. DCT is a well-known technique widely used in image and video processing like JPEG, MPEG-4, H.264, and HEVC. In recent years, APBT was proposed to take the place of DCT in image compression.

In Fig. 4, the response of APBT is compared with DFT and DCT. Fig. 4(a) is a signal sequence in time domain. DFT at the boundaries of the periodic signal is discontinuous which leads to the leakage of energy as shown in Fig. 4(b). Compared with DFT, DCT can reduce high-frequency components in the transform domain by eliminating the effect of discontinuous edge in Fig. 4(c). The reason is that operation of an N-point DCT is equivalent to extending the original N-point data to $2N$ points by mirror extension, followed by $2N$ point DFT of the extended data and their constant magnitude and phase compensation. Obviously, the operation of mirror extension can solve the signal discontinuity problem introduced in the DFT-based interpolation process.

From Fig. 4(d), the energy of APBT transform is more concentrative than that of DCT transform. Therefore, APBT-based channel estimation is expected to have better power concentration in low-frequency region, a better frequency approximation to the frequency response of the original channel impulse and lower aliasing error, than the DFT-based and DCT-based channel estimation. In the following, we will describe the APBT-based channel estimators in detail.

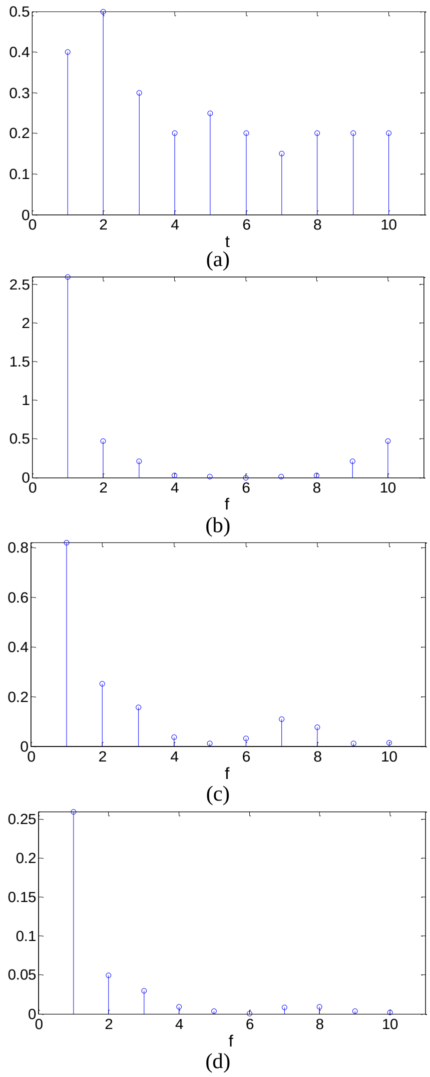


Fig. 4. The response of APBT compared with DFT and DCT: (a) Signal sequence, (b) The response of DFT, (c) The response of DCT, and (d) The response of APBT

C. APBT-Based Channel Estimation

APBT was proposed by Hou *et al.* to solve the blocking artifacts which exist in DCT-JPEG at low bit rate [16]. Because the performance of APBT is better than that of DCT, it is a competitive choice to replace the DCT in some fields. In this paper, APBT-based channel estimation is proposed to replace DCT-based channel estimation.

In conventional DFT-based channel estimation, due to the aliasing error and high-frequency distortion [20], the DCT-based channel estimation is proposed to mitigate it.

But due to the "error floor" existing in DCT-based channel estimation, it can't obtain a better performance at high SNR.

Therefore, for the consideration of better channel estimation result, we use APBT to replace DFT and DCT in conventional channel estimation in this paper. The APBT-based channel estimation is depicted in Fig. 5 and described by the following steps.

Step 1. Similar to DFT-based and DCT-based channel estimation, frequency response $\boldsymbol{Y}_{\mathrm{p}}$ is estimated by LS method. Then instead of performing IDFT and DCT operation, APBT is used to transform the pilot frequency response $\boldsymbol{H}_{\mathrm{p}}$ as shown below:

$$\boldsymbol{h}_{\mathrm{c}} = \boldsymbol{V}\boldsymbol{H}_{\mathrm{p}} \tag{10}$$

where $\boldsymbol{V}$ is the $M \times M$ coefficient matrix of APBT; $\boldsymbol{H}_{\mathrm{p}}$ is the frequency response which is estimated by LS method; $\boldsymbol{h}_{\mathrm{c}}$ is the channel response in APBT-domain, and M is the length of $\boldsymbol{Y}_{\mathrm{p}}$.

Step 2. Padding zero to the APBT-transformed data to obtain the desired signal in the transform domain. From the property of APBT, it can be observed that the energy is mainly in the low-frequency region, and the noise exists in the high-frequency components. So threshold is set in this proposed method. When the response is lower than the threshold, it will be considered as noise, and which should be replaced by zero. The length of $\boldsymbol{h}_{\mathrm{c}}$ should be extended to N by padding zero in the end, after that the extended signal $\boldsymbol{h}_N$ is obtained.

$$\boldsymbol{h}_N(m) = \begin{cases} \boldsymbol{h}_{\mathrm{c}}(m), & m = 0,1,2,\cdots,M-1, \\ 0, & m = M, M+1, M+2, \cdots, N-1. \end{cases} \tag{11}$$

Step 3. Finally, the estimated channel frequency response is obtained by performing inverse APBT.

$$\boldsymbol{H}_N = \boldsymbol{V}^{-1}\boldsymbol{h}_N \tag{12}$$

where $\boldsymbol{V}^{-1}$ is the $N \times N$ coefficient matrix of inverse APBT, N is the length of IDFT/DFT in OFDM.

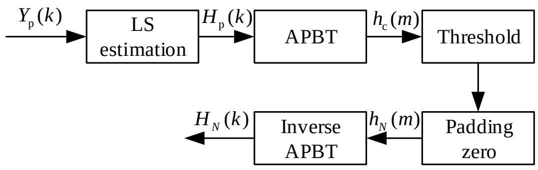


Fig. 5. APBT-based channel estimation

IV. Experimental Results

To evaluate the performance of APBT-based channel estimation for OFDM system, simulations have been performed in Rayleigh fading channels. The additive channel noise is white Gaussian with zero mean and the variance determined by SNR. And the OFDM system parameters used in the simulation are indicated in Table I.

In the experiment, the result shows that the performance of the OFDM is improved by APBT-based channel estimation. BER and MSE are chosen to measure the performance of proposed method. The BER can be expressed as Eq. (13).

$$\mathrm{BER} = \frac{E}{T} \tag{13}$$

where E is the number of error bits, and T is the total number of signals.

TABLE I: SIMULATION PARAMETERS

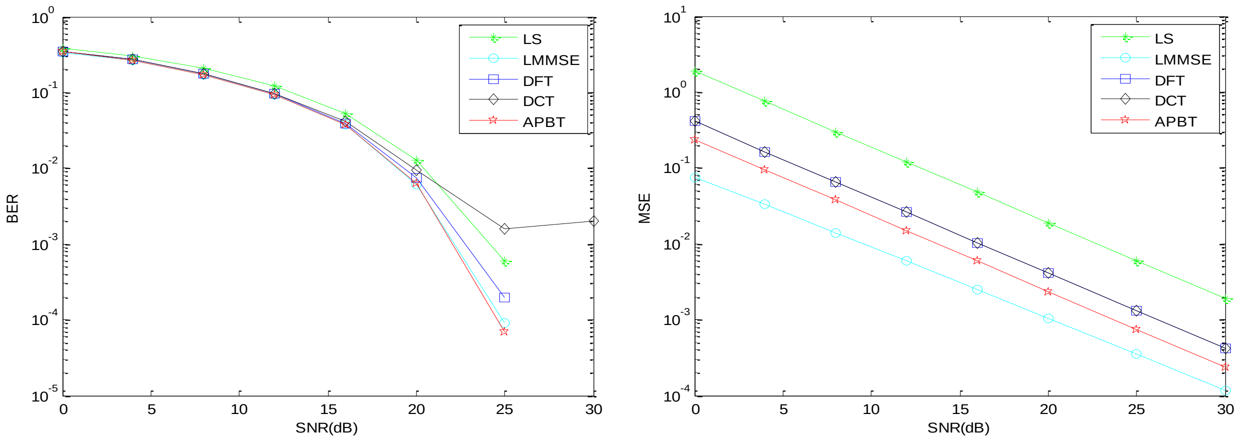
Parameters	Specifications
FFT size	1024
Number of active carriers	128
Pilot ratio	1/8
Guard interval	144
Guard type	Cyclic extension
Bandwidth	10 MHz
Signal mapping	16-QAM, QPSK
Type of pilot arrangement	Comb type
Power spectral density	Jakes' model
Channel model	Rayleigh fading

The APBT-based channel estimation has best performance among all the estimation techniques for 16-QAM and QPSK modulation. In Fig. 6, the BER and MSE of APBT-based channel estimation with 16-QAM modulation are compared with DFT-based and DCT-based estimation and other estimators.

From the result in Fig. 6, it can be observed that the performance of APBT-based channel estimation is better than that of LS, MMSE, DFT-based and DCT-based channel estimation approaches. With the 16-QAM modulation, the "error floor" exists in the DCT-based channel estimation. The DCT-based channel estimation obtains better performance than LS, and DFT-based channel estimation at low SNR, but the estimation effect gets deteriorated with the "error floor" at high SNR. The problem of "error floor" can be solved by the channel estimation based on APBT.

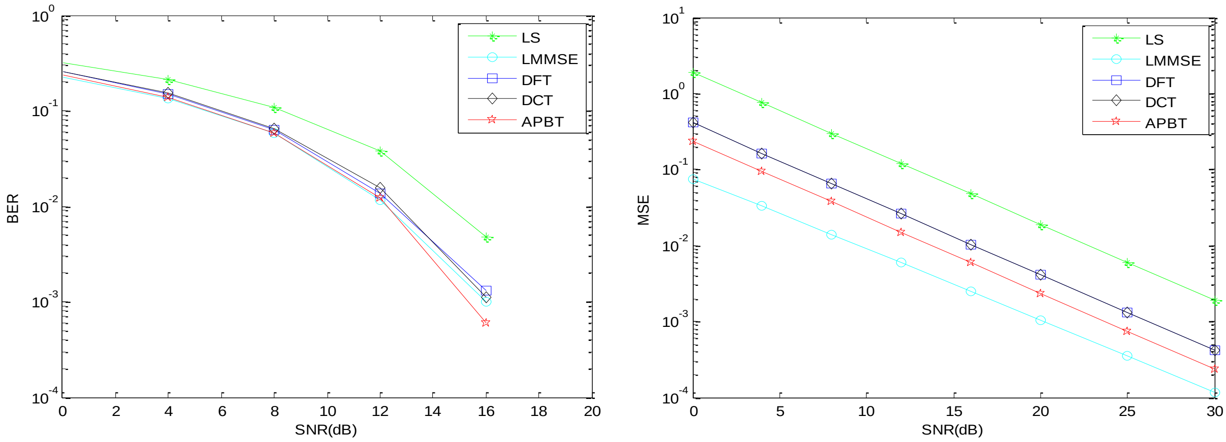
In Fig. 7, the BER and MSE of APBT-based channel estimation with the QPSK modulation are compared with DFT-based and DCT-based estimation and other estimators. From the figure, we can know that APBT-based channel estimation shows similarly better performance compared with other estimators.

From Fig. 6 and Fig. 7, we can conclude that the APBT-based channel estimation has better performance in BER than other channel estimation approaches. But in MSE, the LMMSE is the best. However, the computational complexity of MMSE channel estimation is too high to implement practically.



(a) (b)

Fig. 6. Performance of channel estimation with 16-QAM mapping: (a) BER performance of different estimators and (b) MSE performance of different estimators.



(a) (b)

Fig. 7. Performance of channel estimation with QPSK mapping: (a) BER performance of different estimators and (b) MSE performance of different estimators.

V. Conclusions

On the basis of above discussion, it can be concluded that the APBT-based channel estimation for OFDM is proposed in this paper. Due to that APBT transform has more concentrative energy property than DCT transform, the performance of proposed method is better than that of conventional channel estimations based on DCT and DFT.

Compared with the conventional DFT-based channel estimation and DCT-based channel estimation, the APBT-based channel estimation can solve the leakage energy problem which exists in DFT based channel estimation. In addition, the APBT-based channel estimation does not have the “error floor” which exists in DCT-based channel estimation.

In this paper we use APBT-based channel estimation for OFDM system, and evaluate the performance by BER and MSE. Although the proposed method shows an extensive improvement in terms of system performance, the efficiency of APBT still needs to be improved. These issues will be further researched in the future work.

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