

Design and Research of Channel Estimation for OFDM Systems Based on BEM

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ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is extensively employed due to its advantages in countering channel perturbations, such as multipath fading and frequency selective fading. Nevertheless, the intercarrier interference and sensitivity to synchronization error are the issues that OFDM technology has to confront and resolve. To achieve reliable communication, the accuracy of channel estimation is of particular significance. In this paper, the base extension model is utilized for channel estimation on the MATLAB platform. The Base Expansion Model (BEM) can capture the key characteristics of the channel with fewer parameters, thereby reducing the complexity and enhancing the accuracy of channel estimation. In the system simulation, the signal transmission effect of the current channel is evaluated by comparing the mean error variance and bit error rate under different SNR values. The performances of CE-CEM, P-CEM and GCE-BEM under LS, MMSE and LMMSE are compared, and the best performance of GCE-BEM under LMMSE is obtained, realizing accurate channel estimation.

KEYWORDS

BEM; OFDM; Channel Estimation

1. INTRODUCTION

With the swift development of information technology, people's demands for data transmission rate and communication quality are escalating day by day, especially in the domains of mobile communication, broadband access, and radio and television. High-speed, stable, and efficient communication technology is especially crucial. Wireless signals will encounter various propagation losses and interferences during transmission, particularly frequency selective fading and multipath effect, which severely affect the communication quality. OFDM technology mitigates the effect of frequency selective fading by dividing the wideband signal into multiple narrowband signals and reducing the bandwidth of each sub-signal. Due to its advantages of high spectral efficiency and strong anti-multipath interference, OFDM technology has been widely applied in these fields [1].

However, along with the rapid advancement of the high-speed railway system, the communication system also needs to fulfill the requirements of stability and reliability in a highly mobile environment [2]. In the high-speed environment, OFDM technology will be influenced by the Doppler effect and multipath interference, and the Doppler effect will cause the shift of signal frequency, thereby affecting the orthogonality between subcarriers in the OFDM system and resulting in intercarrier interference. In the high-speed mobile environment, the traditional channel estimation method often fails to achieve the ideal outcome due to the Doppler [3] effect and the rapid time-varying

characteristics of the channel. Therefore, the search for a channel estimation technology that can adapt to the high-speed mobile environment has become one of the current research hotspots.

In recent years, the base extended model, as an advanced channel modeling tool, has garnered extensive attention in the domain of channel estimation [4]. The channel estimation approach based on BEM can capture and assess the characteristics of time-varying channels more precisely, enhancing the communication quality, reliability, and estimation accuracy of OFDM systems. By appropriately selecting the basis functions, the BEM method can adapt flexibly to diverse channel environments, including high-speed movement and frequently altering channel conditions. The performance of the system largely hinges on the receiver's accurate knowledge of the channel state information. Compared to traditional channel estimation methods, the method based on BEM can reduce the computational complexity of channel estimation by lowering the number of required estimation parameters, and is suitable for real-time or resource-constrained communication systems. Accurate channel estimation is a prerequisite for advanced communication technologies such as MIMO-OFDM and beamforming, which can further enhance data transmission rates and system capacity. The channel estimation method based on BEM is conducive to the practical application of these technologies in complex environments. This is particularly significant for OFDM systems in dynamic channel circumstances.

2. SYSTEM MODEL

Orthogonal Frequency Division Multiplexing (OFDM) represents a specialized frequency division multiplexing technique that finds widespread application in contemporary wireless communication systems, including Wi-Fi, LTE, 5G, among others. The core principle underlying OFDM technology involves the segmentation of a high-speed data stream into numerous low-speed data streams, which are subsequently transmitted concurrently on multiple orthogonal subcarriers. This technique boasts several pivotal advantages, notably its efficient spectrum utilization, robust anti-interference capabilities, and efficacy in mitigating multipath fading.

As depicted in Figure 1, the OFDM subcarrier spectrum diagram elucidates the orthogonality among subcarriers from a frequency-domain perspective. Specifically, when a particular subcarrier signal attains its maximum amplitude, the spectral amplitudes of all other subcarrier signals are zero [5]. Consequently, the demodulation of any given subcarrier can proceed without interference from the signals of other subcarriers. Furthermore, the overlapping subcarriers maintain their independence during signal transmission, thereby markedly enhancing the overall bandwidth utilization of the system.

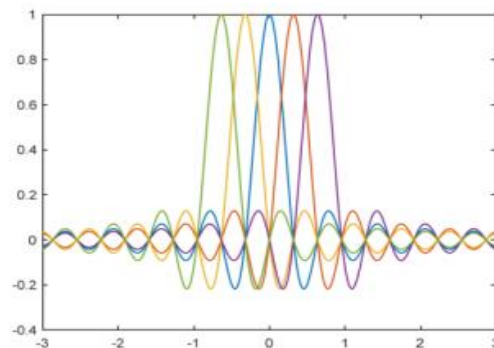


Figure 1. OFDM Subcarrier Spectrum Diagram

The architecture of OFDM is designed to efficiently process and transmit data while resisting various fading and interference in wireless channels. The OFDM system structure can be divided into three main parts: transmitter, channel and receiver [6].

At the sending end, the raw data converts the serial data stream into multiple parallel data streams for simultaneous transmission on multiple subcarriers. Each parallel data stream is mapped to a set of symbols by a certain modulation scheme (e.g. QPSK, 16-QAM, etc.) and then fed into its respective subcarriers. By IFFT processing, multiple sub-signals in frequency domain are converted into time domain signals to generate OFDM symbols. To reduce inter-symbol interference (ISI) caused by multipath, a cyclic prefix is added before each OFDM symbol. The DAC converts the signal into an analog signal, and the signal is up-converted to the wireless frequency band by the up-converter and sent out by the transmitting antenna.

The receiving end receives the signal captured by the antenna and converts the signal from the wireless frequency band back to the baseband through the downconverter. The analog signal is converted to digital signal by ADC, the cyclic prefix of each OFDM symbol is removed, and FFT is executed to convert the OFDM symbol in the time domain to the frequency domain signal, and the frequency domain signal is demodulated (or de-mapped) to restore the original parallel data flow. Merges multiple parallel data streams into a single serial data stream, reverting to the original data format. The data after final processing is sent to the upper layer application to complete the data transmission process. Figure 2 shows the system structure of OFDM.

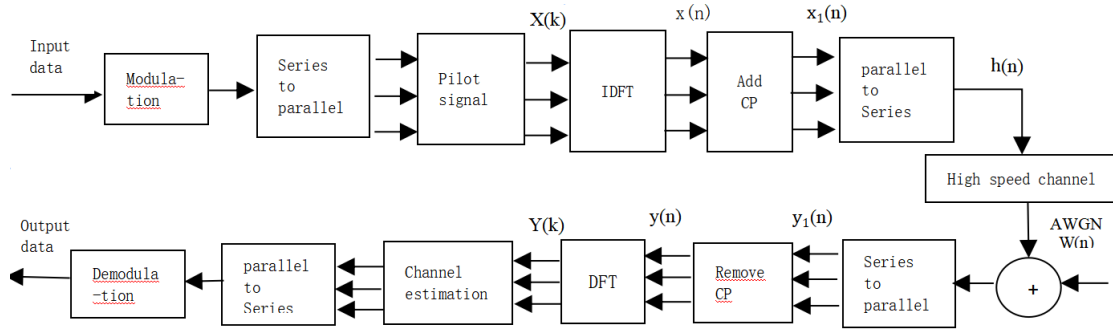


Figure 2. System Structure of OFDM

According to the OFDM framework structure shown in Figure 2, an OFDM system can be assumed to have N subcarriers, and $X_i = [X_i(0), X_i(1) \dots, X_i(N-1)]^T$ subframe contains I OFDM symbols in total. Then, after X_i series of operations such as QAM modulation, pilot insertion and Inverse Fast Fourier Transform (IFFT), the input frequency domain signal X_i can obtain a time-domain signal with length N . Suppose that the time-domain sequence of the n th subcarrier on the i th OFDM symbol sent can be represented as $x_i(n)$. Then the time domain sequence on the i th OFDM symbol is $x_i = [x_i(0), x_i(1) \dots, x_i(N-1)]^T$. As

$$x_i = F^H X_i \quad (1)$$

Among them, $[F]_{n,k} = \frac{1}{\sqrt{N}} \exp\left(-j \frac{2\pi}{N} kn\right)$.

According to the OFDM signal transmission model, after the channel with noise, the output signal can be expressed as

$$y_i = H_i X_i + Z_i \quad (2)$$

Where, the frequency domain vector received on the i th OFDM symbol is

$$y_i = [y_i(0), y_i(1) \dots, y_i(N-1)]^T \quad (3)$$

Z_i is additive Gaussian white noise, the covariance matrix is $\rho = \sigma^2 I_N$, and $H_i \in \mathbb{C}^{N \times N}$ represents the frequency domain response matrix of the channel on the i th OFDM symbol. Then Formula 3 can be expressed as:

$$y_i = F h_i F^H X_i + C_i \quad (4)$$

Where, h_i represents the channel impulse response matrix at the time of the i th symbol [7], $H_i = Fh_iF^H$ can be seen from Formula 4, assuming the channel length is L , then the matrix form of the time-domain channel impulse response h_i is:

$$h_i = \begin{bmatrix} h_i(0,0) & 0 & \cdots & h_i(0,L-1) & \cdots & h_i(0,1) \\ h_i(1,1) & h_i(L,L-1) & \cdots & 0 & \cdots & h_i(1,2) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ h_i(L-1,L-1) & h_i(L-1,L-2) & \cdots & 0 & \cdots & 0 \\ 0 & h_i(L,L-1) & \cdots & h_i(L,0) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_i(N-1,L-2) & \cdots & h_i(N-1,0) \end{bmatrix} \quad (5)$$

The channel impulse response in the OFDM symbol period is time-varying, and the subcarriers are no longer orthogonal under the influence of time-varying channels. Formula 4 shows that the information on each carrier in the received signal includes not only the available signal, but also the interference caused by adjacent carriers under the influence of time-varying channels on the current carrier, that is, the ICI part. Under the influence of Doppler shift in high-speed mobile environment, ICI enhancement affects the accuracy of channel estimation algorithm, and then affects the performance of the whole communication system [2].

3. CHANNEL TECHNOLOGY ALGORITHM

3.1. LS Algorithm

The Least Squares (LS) method estimates the channel in wireless communication systems by minimizing the sum of squares of error between the received signal and the known training sequence sent through the channel model [8]. LS algorithm is simple and easy to implement, and is the simplest algorithm in channel estimation. LS channel estimation minimizes the following functions \hat{H} :

$$\begin{aligned} J(\hat{H}) &= \|Y - X\hat{H}\|^2 \\ &= (Y - X\hat{H})^H (Y - X\hat{H}) \\ &= Y^H Y - Y^H X\hat{H} - \hat{H}^H X^H Y + \hat{H}^H X^H X\hat{H} \end{aligned} \quad (6)$$

Make $\frac{dJ(\hat{H})}{d\hat{H}} = 0$, have:

$$\hat{H}_{LS} = (X^H X)^{-1} X^H Y = X^{-1Y} \quad (7)$$

In OFDM system, LS channel estimation is carried out on each subcarrier, and N is set as the number of subcarriers, then:

$$\hat{H}_{LS} = (X^H X)^{-1} X^H Y = X^{-1Y} \quad (8)$$

The Mean Square Error (MSE) of LS channel estimation is:

$$\begin{aligned}
MSE_{LS} &= E[(H - \hat{H}_{LS})^H (H - \hat{H}_{LS})] \\
&= E[(H - X^{-1}Y)^H (H - X^{-1}Y)] \\
&= E[(X^{-1}Z)^H (X^{-1}Z)] \\
&= E[Z^H (XX^H)^{-1} Z] \\
&= \frac{\sigma_z^2}{\sigma_x^2}
\end{aligned} \tag{9}$$

The MSE of the LS estimation algorithm in Formula 9 is inversely proportional to the signal-to-noise ratio, which means that the LS estimation enhances the noise and is more serious when the channel is deep fading. The LS algorithm is simple and easy to implement. It does not need prior knowledge about the channel statistical characteristics, and only needs to perform channel estimation based on the received signal and the transmitted signal. For small or medium-sized problems, the LS algorithm is usually efficient. However, as the scale of the problem gets larger, the calculations can become computationally heavy and unstable. Although the LS algorithm is simple to implement, it does not take into account the channel noise, the estimation accuracy is low, and the performance is better under the condition of high SNR, and the performance is reduced under the condition of low SNR.

3.2. MMSE Algorithm

The Minimum Mean Square Error (MMSE) algorithm is the expected value of the square that minimizes the difference between the real signal and the estimated signal, the mean square error. In a communication system, signals may be disturbed by noise during transmission [9]. The MMSE algorithm can be used to estimate the original signal, thereby minimizing the error caused by noise. In the system identification problem, MMSE algorithm can be used to estimate the parameters of the system so that the error between the simulated system output based on these parameters and the actual output is minimized [10].

The estimation algorithm based on MMSE takes into account the influence of noise, and has a great improvement in performance compared with LS estimation algorithm. For solution \hat{H}_{LS} of LS algorithm, the weighting coefficient w is used, and the MMSE channel estimation is defined as $\hat{H} = W \tilde{H}$. Channel estimation of MMSE The MSE of \hat{H}_{MMSE} can be expressed as:

$$J(\hat{H}) = E[\|e\|^2] = E[\|H - \hat{H}_{MMSE}\|^2] \tag{10}$$

In MMSE channel estimation, selecting A suitable weighting coefficient w to minimize MSE in Formula 10 can prove that the estimation error vector is orthogonal, that is, it satisfies:

$$\begin{aligned}
E[e \tilde{H}] &= E[(H - \hat{H}) \tilde{H}^H] \\
&= E[(H - W\tilde{H}) \tilde{H}^H] \\
&= E[(H\tilde{H}^H] - WE[(H\tilde{H}^H)] \\
&= R_{H\tilde{H}} - W R_{\tilde{H}\tilde{H}} = 0
\end{aligned} \tag{11}$$

In Formula 11, $R_{H\tilde{H}}$ is the cross-correlation matrix of matrix H and \tilde{H} , and $R_{\tilde{H}\tilde{H}}$ is the auto-correlation matrix of LS channel estimation

$$\tilde{H} = X^{-1}Y = H + X^{-1}Z \tag{12}$$

MMSE channel estimation can be expressed as:

$$\hat{H}_{MMSE} = R_{HH}^{-1} (R_{HH} + \frac{\sigma_n^2}{\sigma_x^2} I)^{-1} \tilde{H} \quad (13)$$

3.3. LMMSE Algorithm

When the number of subcarriers increases, the complexity of MMSE algorithm will increase significantly. LMMSE improves MMSE algorithm by replacing $(X^H X)^{-1}$ with its expected value, and the estimated value is as follows:

$$\hat{H}_{LMMSE} = R_{HH} (R_{HH} + \frac{\beta}{SNR} I)^{-1} \hat{H}_{LS} \quad (14)$$

β is related to the modulation mode. Compared with the MMSE algorithm, the LMMSE algorithm reduces the operational complexity. However, because the LMMSE algorithm is replaced by the average value, it is not accurate enough, so the estimation accuracy is relatively low.

The LMMSE algorithm finds the best linear combination to estimate the unknowns, thereby minimizing the mean square error. Compared with MMSE, LMMSE has the advantage of being more computationally simple and efficient, especially when the signal model and noise model are more complex. Although LMMSE may not be as accurate as MMSE estimates in some cases, it is widely adopted in practical applications due to its simplicity and efficiency. In short, MMSE provides a theoretical optimal estimation framework, while LMMSE provides a linear approximation that is more feasible and easier to implement in practice [11]. Which approach you choose depends on the complexity of the particular problem, the precision required, and the computational resources.

4. HIGH-SPEED CHANNEL MODEL

4.1. Base Extension Model

BEM is a mathematical model used to represent and estimate time-varying channel characteristics in wireless communication. In BEM, the impulse response of a channel is represented as a linear combination of a set of basis functions. These basis functions can be any set of complete functions, such as Fourier basis, polynomial basis, etc., which are used to approximate the changes of the channel in a specific time and frequency range [12]. The time-varying properties of the channel are captured by the coefficients of these basis functions, which reflect the characteristics of the channel with respect to time and frequency [13]. The base extension model is particularly important in channel estimation of OFDM systems, because it can effectively describe and deal with time-varying characteristics of multi-path channels, and improve the accuracy and efficiency of channel estimation.

The base extension model provides an efficient channel estimation framework, but its performance is strongly dependent on the selected basis function and model parameters [14]. Improper selection of basis functions or inaccurate parameter Settings may result in poor estimation performance. This thesis mainly studies three kinds of base extension models, complex exponential base, polynomial base and generalized complex exponential base.

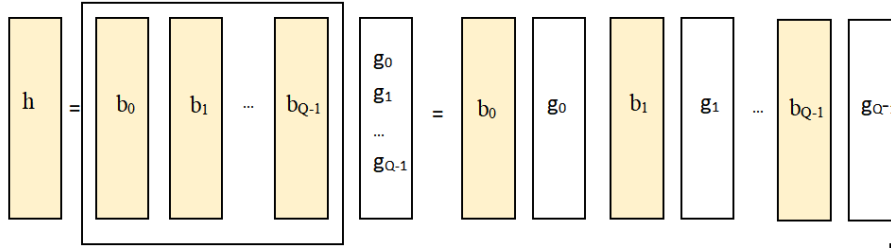


Figure 3. Schematic Diagram of BEM Implementation

4.2. CE-BEM

The Complex Exponential Basis Expansion Model (CE-BEM) is based on the complex exponential function as the basis function to represent the change of channel characteristics with time, which is especially suitable for simulating time-varying channels in high-speed mobile communication environment [15]. In CE-BEM, the time-varying properties of a channel can be represented by a linear combination of complex exponential basis functions. These basis functions correspond to different frequency components of the channel shock response, which enables the model to adapt to and accurately describe the rapid changes of the channel in time [16]. Because this method can accurately represent channel changes with fewer parameters, it can significantly reduce the computational complexity of channel estimation. Is the most basic base extension model, and the expression of its base function is shown in Equation 15:

$$\mathbf{b}_q(n) = e^{\frac{j2\pi (q\frac{Q}{2})n}{N}}, n=0, n=1, \dots, N-1 \quad (15)$$

CE-BEM is a Fourier infrastructure mode fast time-varying channel whose period is the same as OFDM symbol length [17]. It strictly samples the Doppler spectrum in the frequency domain and approximates the channel change in the current OFDM symbol transmission time with the sampled frequency point value. Due to the low frequency resolution of CE-BEM basis function, spectrum leakage occurs when the channel is in a slow time-varying state, resulting in Gibbs phenomenon, which affects the channel fitting performance.

4.3. P-BEM

The Polynomial Basis Expansion Model (P-BEM) selects a suitable set of polynomial basis functions and optimally approximates the objective function or signal by adjusting the coefficients before these basis functions.

The polynomial base extension model can be used for signal filtering, compression and feature extraction. On the basis of polynomials, the projection expansion of the channel in the Taylor subspace is carried out. The expression of the basis function is shown in Equation 16:

$$\mathbf{b}_q(n) = (n - \frac{N}{2})^q, n=0, n=1, \dots, N-1 \quad (16)$$

Although the P-BEM implementation is also relatively simple, it is very sensitive to Doppler shift and is only suitable for scenes with low moving speed.

4.4. GCE-BEM

The Generalized Complex Exponential Base Extension Model (GCE-BEM) [18] uses a method of multiplying the frequency of the basis function by a coefficient less than 1, so that the maximum frequency of the basis function of the complex exponential base extension model is less than the maximum Doppler shift. Using more intensive frequency sampling to make up for the edge error of

the complex exponential base expansion model can effectively reduce the influence of the high frequency basis function and reduce the modeling error, and the sampling frequency is an integer multiple of the symbol length. Compared with other models, GCE-BEM model has the lowest sensitivity to estimation error, and is more suitable for systems with large Doppler shift estimation error.

GCE-BEM adds an overmining factor K on the basis of CE-BEM, so that the sampling interval becomes $1/KN$ and the sampling frequency becomes more intensive. The expression of the basis function is shown in Equation 17:

$$\mathbf{b}_q(n) = e^{\frac{j2\pi \left(q - \frac{Q}{2}\right) n}{KN}}, n = 0, n = 1, \dots, N - 1 \quad (17)$$

In this case $Q \geq 2\lceil v_d KN \rceil$, and then approximate the value of $Q+1$ near 0. When the overextraction factor is 1, GCE-BEM is equivalent to CE-BEM.

5. SIMULATION ANALYSIS

5.1. System Parameters

In this section, the new method will be simulated and analyzed to verify its predictive performance. This paper considers a single in single out OFDM system. In the simulation process, the specific simulation parameters are given in Table 1.

Table 1. System Simulation Parameter Settings

System Parameters	Numerical value
Carrier number	64
Number of OFDM symbols	50
Cyclic prefix	8
Pilot interval	8
Modulation mode	QPSK
Cycle number	10
Signal length	1024
Multipath component	8
Overextraction factor	2
Quantity of basis function	4

5.2. Influence of Different Channel Estimation Algorithms on the System

FIG. 4 shows the BER performance comparison diagram of three channel estimation algorithms in the OFDM system model, and FIG. 5 shows the MSE performance comparison diagram of three channel estimation algorithms in the OFDM system model. Set the number of carriers to 64, the number of symbols to 50, the cycle prefix to 8, the pilot interval to 8, using QPSK modulation, cycle 10 times.

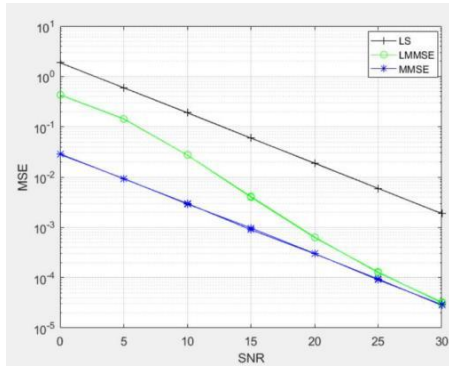


Figure 4. BER Performance

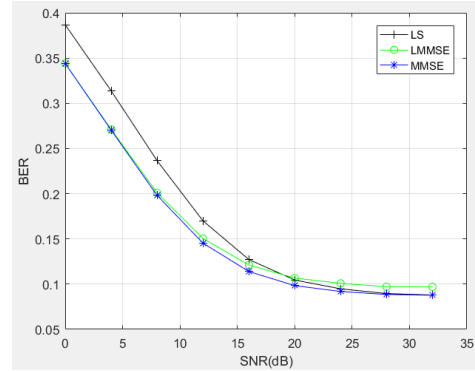


Figure 5. MSE performance

The results show that MMSE algorithm has the best performance, followed by LMMSE algorithm and LS algorithm has the worst performance. By analyzing the theoretical knowledge, the following conclusions can be drawn: LS channel estimation algorithm is simple, but sensitive to noise. The MMSE channel estimation algorithm can effectively suppress the noise interference, and its performance is better than LS channel estimation algorithm, but it needs to solve the inverse matrix, which is difficult to implement in hardware. Compared with MMSE algorithm, LMMSE algorithm can reduce the operation complexity, but because LMMSE algorithm is replaced by average value, it is not accurate enough, so the estimation accuracy is relatively low.

5.3. Impact of Different BEMs on the System

5.3.1. Performance Comparison under LS Channel estimation Algorithm

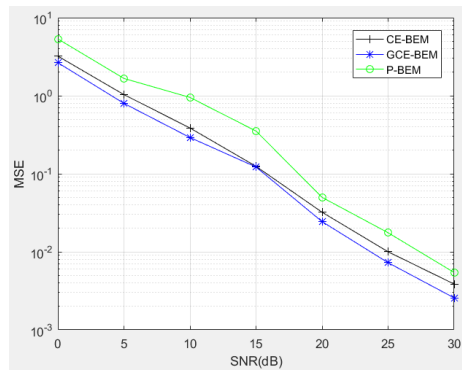


Figure 6. MSE of Three BEMs

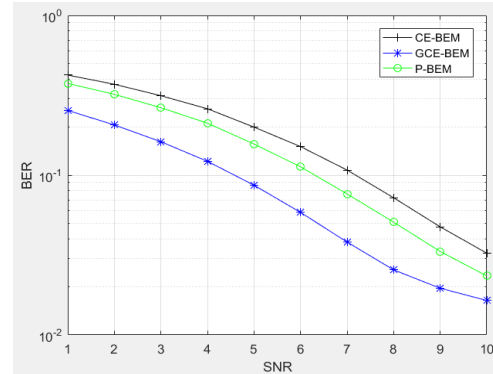


Figure 7. BER of Three BEMs

As shown in Figure 6, under the LS algorithm, when the oversampling factor of GCE-BEM is set to 2, the estimation error of P-BEM is the largest, followed by CE-BEM, and the estimation error of GCE-BEM is the smallest. When the SNR is equal to 15dB, the estimation error of CE-BEM and GCE-BEM is the same. It can be seen that double over-sampling of CE-BEM can effectively improve the estimation error and reduce the problem of spectrum leakage. Figure 7 shows that GCE-BEM has the best effect under LS algorithm.

5.3.2. Performance Comparison under MMSE Channel Estimation Algorithm

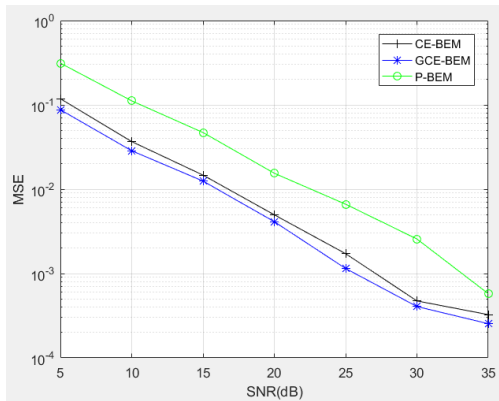


Figure 8. MSE of Three BEMs

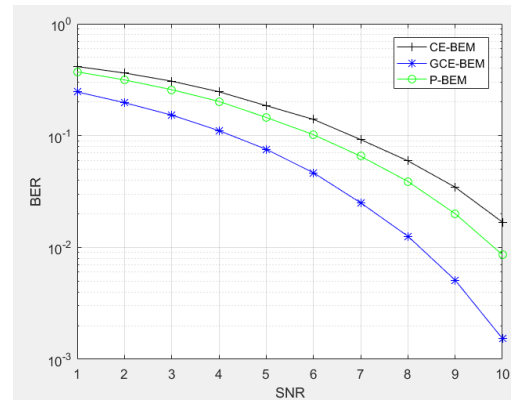


Figure 9. BER of Three BEMs

Figure 8 and Figure 9 respectively show the curves of mean error variance and bit error rate of CE-BEM, GCE-BEM and P-BEM under the MMSE algorithm. It can be seen that GCE-BEM is the best, followed by CE-BEM, and P-BEM has the largest estimation error. With the increase of signal-to-noise ratio, the performance of MSE and SNR based on the three base extension models is gradually improved.

5.3.3. Performance Comparison under LMMSE Channel Estimation Algorithm

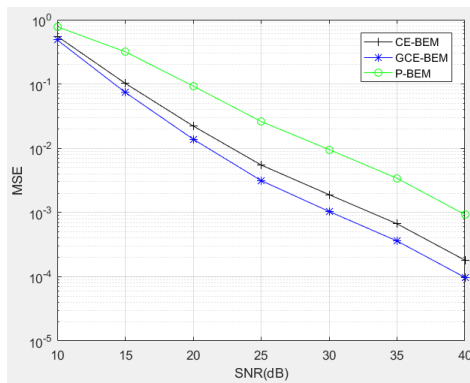


Figure 10. MSE of Three BEMs

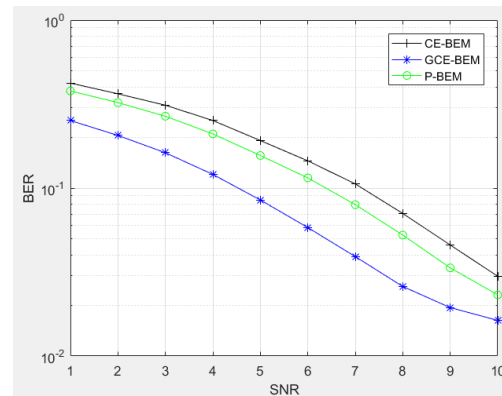


Figure 11. BER of Three BEMs

Figure 10 shows the curve of the mean error variance of CE-BEM, GCE-BEM and P-BEM under the LMMSE algorithm. It can be seen that GCE-BEM is the best, followed by CE-BEM, and P-BEM has the largest estimation error. With the increase of SNR, the performance of MSE based on the three base extension models is gradually improved. When the SNR is 30dB, the mean error variance of GCE-BEM under LMMSE algorithm drops to 10^{-4} . Figure 11 shows that GCE-BEM has the best effect under the LMMSE algorithm. It can be seen that the GCE-BEM under the LMMSE algorithm is optimal.

6. CONCLUSION

This paper studies the application of base extension model in the field of channel estimation, introduces the basic principle and deduces the algorithm formula, builds the channel estimation model using MATLAB platform, and analyzes the performance of CE-BEM, P-BEM and GCE-BEM under different algorithms. Through the analysis and simulation of the base extension model, the following conclusions are drawn: Because CE-BEM truncates the original sequence, the error of the channel edge model is obvious, resulting in the amplitude and phase estimation error of the channel gain on the edge part of the sequence is too large, resulting in edge spectrum leakage and Gibbs phenomenon, which affects the channel fitting performance. However, P-BEM is very sensitive to Doppler shift

and is not suitable for high-mobility wireless communication environments. Compared with other models, GCE-BEM model is the least sensitive to the estimation error, and is more suitable for the system with large Doppler shift estimation error, so as to obtain the channel estimation optimization scheme of OFDM system in high-speed scenarios.

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