Applied Mathematics & Information Sciences
An International Journal

Effect of Group Delay on Channel Estimation Performance in OFDM System

XIA LEI[1], *YAMIN SONG*[1], *XIRU YAO*[1], *BINHONG DONG*[1] *and MAOZHU JIN*[2,*]

[1] National Key Laboratory of Communications, University of Electronic Science and Technology of China, Chengdu, 610054, P.R. China
[2] Business School of Sichuan University Chengdu, 610065, P.R. China

Received: Nov. 17, 2011; Revised Jan. 14, 2012; Accepted Feb. 26, 2012

Abstract: The OFDM (Orthogonal Frequency Division Multiplexing) channel estimation technologies are discussed and researched in this paper. The effect of group delay on the channel estimation technologies of OFDM System is researched. After thorough theory analysis and simulation programs, the conclusion that under slow and flat circumstance, the effect of group delay on the channel estimation algorithms of OFDM System is considerably small has been made.

Keywords: OFDM, Interference Elimination, Channel Estimation, Group Delay

1. Introduction

Key technologies related to OFDM such as carrier frequency synchronization, channel estimation, etc., have achieved remarkable results in the theory and practice. Many domestics and foreign literatures on these subjects could be consulted [1–4]. However, there is little research on the filter, and even the channel group delay characteristics of the OFDM system.

Channel estimation is also affected by group delay in practical OFDM system. In this paper, we mainly investigate the causes of group delay and its impact on channel estimation in OFDM system. A reasonable model on group delay is proposed and computer simulation demonstrates that the slow group delay has no obvious impact on channel estimation of OFDM system [5, 6].

2. Group Delay Character of Wideband Short Wave Channel

Short-wave communication is used as one important mean of communication for mature technology, long-range communication, small size and suitability for working on moving vehicle, ship and airplane. Especially, in recent years a series of achievement on wave transmission, ionosphere character and channel character research and technology such as adaptive frequency selection, adaptive equalization and adaptive rate control, has made breakthrough progress in combating the multipath fading, improving communication quality and raising spectrum utilization and communication availability rate, so made short-wave communication into a new high-quality information transmission stage. Except for capability and bandwidth, the adaptive communication quality of short-wave communication can sustain comparison with that of satellite communication.

2.1. Group delay character of the short-wave channel model

Radio waves travel through the open natural space and the earth. So both the universal and the magnetic field of the ground, the ocean, the atmosphere and the earth can impose effect on the transmission characteristics of radio waves. The wavelength of short wave is relatively longer, 10m ˜ 100m, and the corresponding frequency is low, 3MHz ˜ 30MHz. The sky-wave and ground-wave are two main transmission mode of radio waves in this band.

The transmission character of ground-wave is that the waves can be affected and attenuated by the ground electrical conductivity σ and the relative dielectric constant

* Corresponding author: e-mail: jinmaozhu@scu.edu.cn.

ε . Generally, the bigger values σ and ε have, the less is the transmission loss. So the propagation distance of the ground-wave on the sea is longer than that of on the ground. The propagation loss increases at higher frequencies. The propagation distance is merely tens of kilometers even at the lower short-wave frequency when the transmission power is not very large.

The shy-wave can be transmitted over a long distance though ionosphere reflection one or more times. Generally, the maximum ground transmission distance is 4000km one reflection, and thousands of kilometers multiple reflections, even around the earth. Therefore, transmission through reflection of ionosphere is the main transmission forms of short-wave communication. That is the precise reason why the structure, characteristics and change rule of ionosphere have significant influence on the structure, signal form, modulation style, processing method and application range of short-wave communication.

The ionosphere is part of the upper atmosphere whose height ranges from 50km to 1000km above ground. A great number of free electrons and ions in this zone will change the speed of radio waves, reflect, refract and scatter radio waves. These electrons and ions rotate the polarization plane and absorb energy. The ionosphere is caused by solar ultraviolet radiation and X-ray. The sun high-energy charged particles and the galactic cosmic radiation also have significant influence on the ionosphere. The different ability of atmospheric radiation through the ionosphere in different areas and the diurnal and seasonal changes of the sun radiation make an obvious distinction between the ionosphere according to electron density, latitudes and longitudes. Thus, different density layers is formed.

It is pointed out in the theory of radio waves propagation in the ionosphere that only the high frequency radio waves from the high electron density of the ionosphere can be reflected back into the ground. And whether the wave can be reflected is also related with the incident angle. So radio waves at different frequency propagate through different paths and the corresponding ground propagation distance is also different. Waves at a very high frequency will penetrate the ionosphere without reflected to ground. Waves at a very low frequency will not assure the communication quality because of the very high loss. That is to say a maximum available frequency and a minimum available frequency define an interval. Only using waves at a frequency in the interval with a certain incident angle can communication systems work normally. The so-called silent region is a circular region which is not far away from the transmitter and can't be reached by the sky-wave because the incident angle is too big or the ground-wave because the distance is too long.

The ionospheric electron and ion density is not the same throughout a space. The unevenness of density will cause bad effects like multipath, fading, phase fluctuation, Doppler shift and so on. But not only will the unevenness cause serious problems in communications. The ionosphere can be disturbed suddenly by processes without certain strict rules like mutation of the ionization source like solar flare, the non-equilibrium dynamic process, the unstable magnetic flow dynamic process and activities of human and nature like ground nuclear test, high altitude nuclear test, high power short-wave radar heating and so on. All these regular or random burst processes will bring serious influences on the transmission of short waves even outage in short-wave communications.

In general, the short-wave channel is a changeable dispersion channel in time, frequency and space domain. The instability of short-wave channel cause narrowband, low capacity, low bit rate and serious interference in short-wave communications.

The group delay is the distinct feature of the wideband short-wave channel influenced by its transmission characteristic. The group delay increases with the increasing propagation time signal through the medium in ionosphere and is proportional to the electron density. Different frequency components are reflected by the ionosphere at different heights. So the propagation distances of different frequency components are different. Thus the time delays when different frequency components are received are different [7].

The Watterson model recommended by CCIR is widely used as a short-wave channel model [8].But it can only describe the narrowband channel with an efficient bandwidth less than 12KHz. The model assumes the amplitude of channel fading to be of Rayleigh distribution and Doppler spread of each mode to be of normal distribution. The shape of delay spread is not modelled in the model and the time delay for each mode is not considered in practical use.

The group delay is realized though the Watterson model whose output end is followed by a filter which has quadratic phase response and flat amplitude response proposed by Milson [9].The model is mainly applied in Direct Sequence Spread Spectrum (DSSS) communications with NVIS transmission mode and assumes X mode can be separated from O mode. But when X mode can't be separated from O mode, the filter must be redesigned. From the physical view, the model has inherence drawbacks because the different frequency components in the band are correlative whereas any components with an interval of several KHz will not correlative in practical engineering application.

Vogler and Hoffmeyer proposed a wideband short-wave channel model in a classic paper published on Radio Science in 1993 [10].Channel transfer function, pulse response and scattering function were deducted through experimental data and then the mathematical model was formed.

ITS model proposed by ITS in 1997 is another widely used reference model which is based on Vogler model [11]. The model is applicable to describe both wideband and narrowband channel.

The basic idea of ITS model is similar to that of Vogler model:

$$h(t,\tau) = \sum_n h_{pn}(t,\tau) = \sum_n \sqrt{P_n(\tau)} D_n(t,\tau) \psi_n(t,\tau) \quad (1)$$

Where $p_n(\tau)$ is distribution of delay power spectrum, $D(t,\tau)$ determines phase function and describes Doppler shift, $\psi_n(t,\tau)$ is the random modulation function which describes Doppler spread process.

2.2. OFDM in short-wave communication

Short-wave channel is a typical channel of variable parameter. The transmission reliability of short-wave channel is poor. The available working frequency need often to be replaced. Serious multi-path fading exists in short-wave channels. All of these characters will impose effects on the short-wave communication system. Especially for short-wave digital signal transmission system high bit rate is not reachable often.

The realization of high bit rate in short-wave communications must rely on wideband technologies like Fast Frequency Hopping (FFH), Direct Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multiplexing (OFDM) which are used widely nowadays. All these technologies can spread the spectrum in some form. In recent years OFDM has emerged for its inherent character of combating multipath fading and narrowband interference. So OFDM is very appropriate for short-wave communications. High bit rate transmission in wideband short-wave communication can be realized by utilizing OFDM. Capacity, reliability and anti-interfere ability of the short-wave system can be increased greatly. The bottleneck of low transmission rate is settled. Therefore, the application of OFDM in short-wave systems becomes a trend [12].

In summary, the application of wideband OFDM in short-wave systems becomes extensive gradually. The group delay is the distinct character of the wideband short-wave channel. But the study on this aspect is very little at present.

3. The Group Delay of OFDM System

Group delay is the delay of wave groups caused by the channel which group signal is transmitted through an a whole. In the single frequency system, the group delay refers to the phase delay, namely, there is no group delay for the single frequency signal transmission.In physics sense, group delay at a certain frequency means the transmission time of a narrowband signal through the system and network with the certain frequency as the center of its band, which equals the first order differential of phase characteristic in the numerical [5].

If we divide the signal bandwidth into numerous small enough intervals, i.e. $\Delta\omega \to 0$, the amplitude $A(\omega)$ can be considered as constant and the phase $\varphi(\omega)$ as linear, then we have [13]

$$\tau_g = \lim_{\Delta\omega \to 0} \frac{\Delta\varphi(\omega)}{\Delta\omega} = \frac{d\varphi(\omega)}{d\omega} \qquad (2)$$

Equation(2)is the mathematical representation of group delay, which is defined as the derivative of phase to angular frequency.

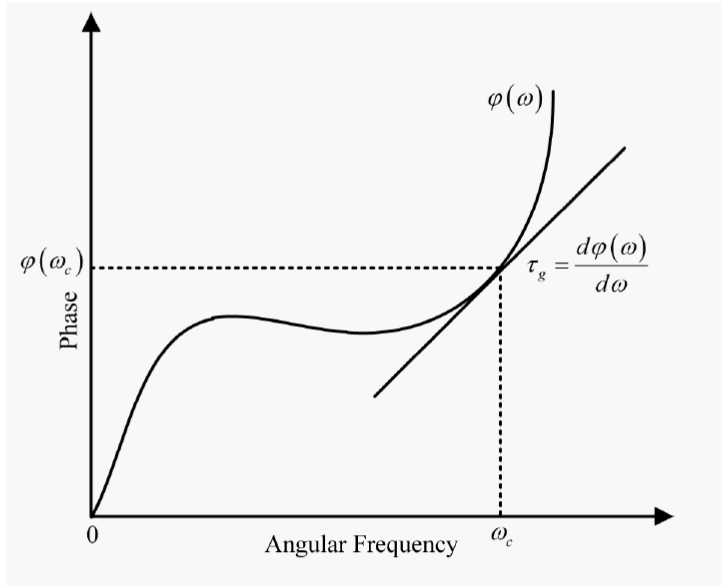


Figure 1 Geometric meaning of group delay in the phase frequency character curve.

Geometric meaning of group delay in the phase frequency character curve is shown in Figure.1.

Most studies on channel estimation assume the group delay is constant, i.e. phase is linear to angular frequency so it will not affect the estimation of channel. However, the group delay in practical OFDM system is not constant, thus, a non-constant group delay model need to be designed and simulation need to be ran to validate the impact of group delay on the performance of OFDM system.

Non-constant group delay can cause ICI (ICIInter Channel Interference) and affect the orthogonal of OFDM system, thus , BER increase [14].

Firstly, the following equations are obviously correct. After modulation and s/p conversion, the transmission signal is fed to the Inverse Fast Fourier transform (IFFT) filter to realize orthogonal. In the ith OFDM symbol block, $X_{i,k}$ denotes the complex-valued symbol in frequency domain. The time domain transmitted data sample, in ith OFDM symbol block, is given by

$$x_{i,n} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_{i,k} e^{\frac{j2\pi nk}{N}}, 0 \le n \le N-1 \qquad (3)$$

At the receiver, after the cyclic prefix is discarded, the received signal can be represented as

$$y_n = x_n \otimes h(n) \qquad (4)$$

From definition of convolution, we can get

$$y_n = \sum_{m=0}^{N-1} x(n-m) * h(m) \qquad (5)$$

Substituting (2) into (4) gives

$$y_n = \sum_{m=0}^{N-1} \left(\sum_{i=0}^{N-1} X_i e^{j2\pi \frac{i(n-m)}{N}} \right) \cdot h(m) \tag{6}$$

After Fourier Transform, system time domain response is the complex function of the amplitude and phase (to simplify the analysis, all amplitude are set to 1). Thus channel time domain response should be written as the IFFT of phase item, namely

$$h(m) = \sum_{i=0}^{N-1} e^{j2\pi \frac{im}{N}} e^{j\varphi(i)} \tag{7}$$

So, the received signal can be written as

$$\begin{aligned} Y_n &= \sum_{k=0}^{N-1} e^{-j2\pi \frac{nk}{N}} y_k \\ &= \sum_{k=0}^{N-1} e^{-j2\pi \frac{nk}{N}} \left[\sum_{m=0}^{N-1} \left(X_i e^{j2\pi \frac{i(k-m)}{N}} \right) \right. \\ &\quad \left. \bullet \left(\sum_{i=0}^{N-1} e^{j2\pi \frac{im}{N}} e^{j\varphi(i)} \right) \right] \end{aligned} \tag{8}$$

which is different from the derivation in [14].

3.1. Channel Group Delay Model

Refer to the general definition of filter group delay, we give the mathematical representation of group delay as [5]

$$\tau_g = -\frac{d\Phi(\omega)}{d\omega} second \tag{9}$$

Where "-" denote that output signal always lag behind input signal. Group delay defined in Equation(9) is also named "absolute group delay".

In the presence of group delay distortion, filter phase characteristic is absolutely not a straight line but a curve, which is a function of frequency deviation [15]

$$\Phi(\omega) = b_1(\omega - \omega_c) + b_2(\omega - \omega_c)^2 + b_3(\omega - \omega_c)^3 + \cdots \tag{10}$$

Assume the amplitude of frequency response is 1, then frequency response can be written as

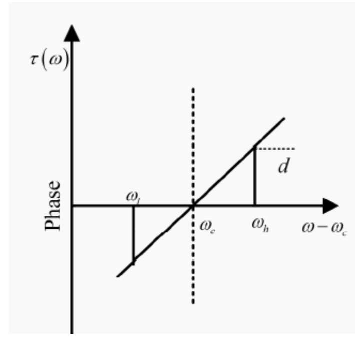
$$H(j\omega) = e^{j\Phi(\omega)} \tag{11}$$

From the first order derivative of $\Phi(\omega)$, we can get

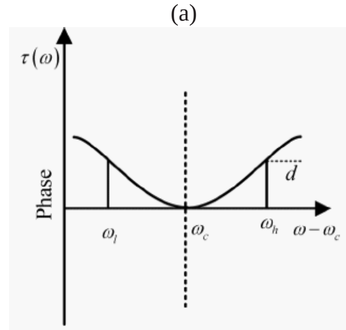
$$\tau(\omega) = b_1 + 2b_2(\omega - \omega_c) + 3b_3(\omega - \omega_c)^2 + \cdots \tag{12}$$

Where $b_1\tilde{\ }b_3$ are every order phase coefficients. The first term is the constant term which will not introduce distortion to signals. The second term is the linear distortion. The third term is the parabolic distortion. The high order components have little impact on distortion so can be ignored [16].

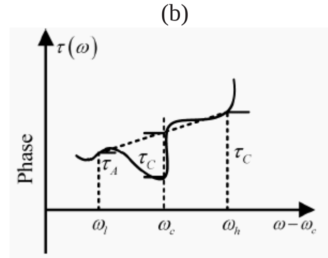
The figure of the linear distortion, parabolic distortion and asymmetric distortion is show in Figure.2 (a) (b) (c) respectively.



(a)



(b)



(c)

Figure 2 The figure of (a) the linear distortion (b) parabolic distortion (c) asymmetric distortion.

Generally, the linear distortion can be defined as [16]

$$\tau_{gd} = \frac{d}{B}(ns/MHz) \tag{13}$$

The parabolic distortion can be defined as

$$\tau_{gd} = \frac{\tau_c}{B^2} \tag{14}$$

For asymmetric parabolic group delay, the linear distortion can be defined as

$$\tau_{gd} = \frac{\tau_B - \tau_A}{B}(ns/MHz) \tag{15}$$

The parabolic distortion can be defined as

$$\tau_{gd} = \frac{\tau_C}{B^2}\left(ns/MHz^2\right) \tag{16}$$

Where d, τ_A τ_B respectively is the distortion value of linear, parabolic and asymmetric parabolic group delay in the edge of bandwidth, τ_C is the group delay value in the center of bandwidth. $\omega_h - \omega_l$ is the passing band of the filter, ω_h is the maximum angular frequency in passing band. ω_l is the minimum angular frequency in passing band.

3.2. Impact of Group Delay on Channel Estimation

Based on the above simplified channel group delay model, and different from the theoretical derivation in [14], a degraded and primitive channel frequency response and system model is used to estimate channel in the presence of group delay to validate the impact of group delay on channel estimation.

The known transmission signal after FFT is represented as

$$x_n = \sum_{i=0}^{N-1} X_i e^{j2\pi \frac{nk}{N}} \tag{17}$$

Then the received signal in frequency domain can be written as

$$\begin{aligned} Y_n &= \sum_{k=0}^{N-1} y_n e^{-j2\pi \frac{nk}{N}} \\ &= \sum_{k=0}^{N-1} x_k \otimes h_k e^{-j2\pi \frac{nk}{N}} \\ &= \sum_{k=0}^{N-1} e^{-j2\pi \frac{nk}{N}} \left(\sum_{m=0}^{N-1} x_m h_{k-m} \right) \\ &= \sum_{m=0}^{N-1} x_m \left(\sum_{k=0}^{N-1} e^{-j2\pi \frac{nk}{N}} h_{k-m} \right) \end{aligned} \tag{18}$$

The frequency channel response after FFT is

$$H_n = \sum_{k=0}^{N-1} e^{-j2\pi \frac{nk}{N}} h_k \tag{19}$$

So the FFT result of h(n-m) is $e^{-j2\pi nm} \cdot H_n$.

Then equalization (18) can be simplified as

$$\begin{aligned} Y_n &= \sum_{m=0}^{N-1} x_m \left(e^{-j2\pi \frac{nm}{N}} H_n \right) \\ &= H_n \cdot X_n \end{aligned} \tag{20}$$

The above derivation shows that no matter what the expression of frequency channel response containing group delay is, as long as the group delay model appropriate for the system could be found, the channel estimation algorithm can be used as usual and we can see the impact of group delay on channel estimation in the presence of group delay.

Using the simplified channel group delay model and maximum likelihood LS channel estimation algorithm, also the FFT interpolation, we can get the following deduction [17].

The received signal in frequency domain with AWGN interference can be represented as

$$\mathbf{Y} = \mathbf{HX} + \mathbf{W} \tag{21}$$

Then the estimation of channel frequency response using the maximum likelihood LS algorithm can be given by

$$\hat{\mathbf{H}}_p = \mathbf{Y}_p \mathbf{X}_p{}^{-1} \tag{22}$$

Where subscript p denote the pilot index.

After the Inverse Fast Fourier Transformation, $\hat{\mathbf{h}}_p$ can be got and then $\hat{\mathbf{h}}_p$ is fed to N-point FFT interpolation, channel frequency response in all subcarriers can be obtained as

$$\tilde{\mathbf{H}} = fft\left(\hat{\mathbf{h}}, N\right) \tag{23}$$

The values of key parameter b_1, b_2, b_3 in the group delay model described by equalization (12) change with the varying channel and environment. In this paper, we choose a group of typical values in OFDM system for analysis.

When the group delay respectively is constant, linear, parabolic and asymmetric parabolic, group delay and channel frequency response can be represented as follow.

1) When the group delay is constant , then group delay $\tau = 0.026$, the channel frequency response is

$$\begin{aligned} \mathbf{H} &= e^{j\Phi(\omega)} \\ &= e^{j*0.026(2\pi\Delta fn - 2\pi f_c)} \\ &= e^{j*0.026\left(2\pi\cdot\frac{1}{N}\cdot n - 2\pi\cdot\frac{1}{N}\cdot\frac{N}{2}\right)} \end{aligned} \tag{24}$$

2) When the group delay is linear, then group delay $\tau = 0.026\,(\omega - \omega_c)$, the channel frequency response is

$$\begin{aligned} \mathbf{H} &= e^{j\Phi(\omega)} \\ &= e^{j*0.013(2\pi\Delta fn - 2\pi f_c)^2} \\ &= e^{j*0.013\left(2\pi\cdot\frac{1}{N}\cdot n - 2\pi\cdot\frac{1}{N}\cdot\frac{N}{2}\right)^2} \end{aligned} \tag{25}$$

3) When the group delay is parabolic, then group delay $\tau = 0.011(\omega - \omega_c)^2$, the channel frequency response is

$$\mathbf{H} = e^{j*\frac{0.011}{3}\left(2\pi\cdot\frac{1}{N}\cdot n - 2\pi\cdot\frac{1}{N}\cdot\frac{N}{2}\right)^3} \tag{26}$$

4) When the group delay is asymmetric parabolic, then group delay $\tau = 0.026 + 0.026\,(\omega - \omega_c) + 0.011(\omega - \omega_c)^2$, the channel frequency response is

$$\begin{aligned} \mathbf{H} &= e^{j*\left[0.026\left(2\pi\cdot\frac{1}{N}\cdot n - 2\pi\cdot\frac{1}{N}\cdot\frac{N}{2}\right)\right]} \\ &\bullet e^{j*\left[0.013\left(2\pi\cdot\frac{1}{N}\cdot n - 2\pi\cdot\frac{1}{N}\cdot\frac{N}{2}\right)^2\right]} \\ &\bullet e^{j*\left[\frac{0.011}{3}\left(2\pi\cdot\frac{1}{N}\cdot n - 2\pi\cdot\frac{1}{N}\cdot\frac{N}{2}\right)^3\right]} \end{aligned} \tag{27}$$

4. Simulation Results and Analysis

Simulation parameters are as follow. The number of subcarriers denoted by N is 1024, the number of pilot denoted by K is 256, and comb pilot pattern is used. QPSK modulation is considered.

Figure.3 shows the minimum square error (MSE) performance of channel estimation under three group delay type, namely, constant ($\tau = 0.026$), constant and linear, linear ($\tau = 0.013$) type group delay. The three curves in

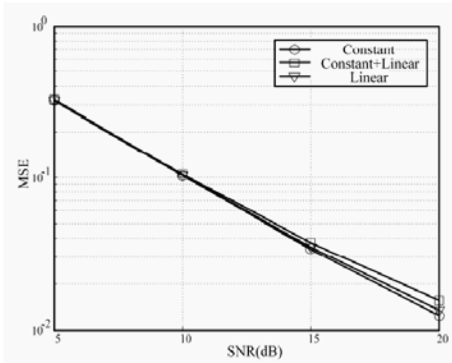


Figure 3 MSE performance of channel estimation under three group delay type.

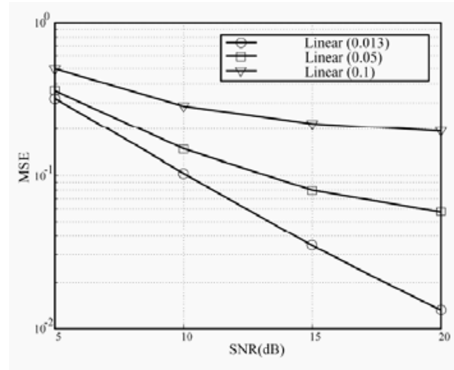


Figure 5 MSE performance of channel estimation under linear type group delay.

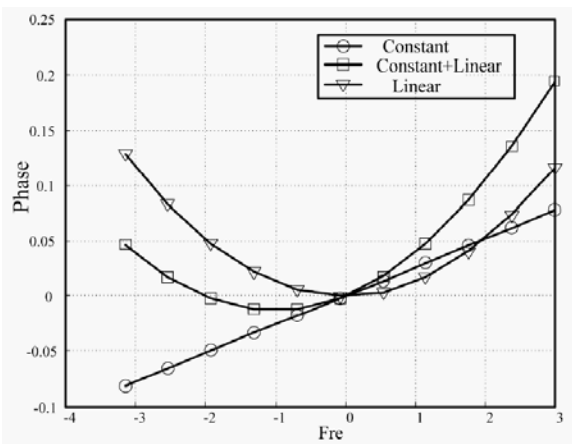


Figure 4 phase curve of the three type group delay.

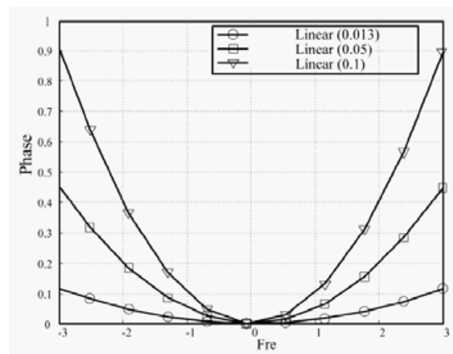


Figure 6 Phase variation curve of constant type group delay with increscent coefficient.

fig.5 are very close we can see that the linear characteristic of group delay has little impact on the channel estimation.

Figure.4 shows the phase curve of the above three type group delay. From the simulation result we can conclude that compared with the phase curve of constant type group delay, although the other two phase curve has substantial bending but this characteristic has still not caused impact which can't be ignored on channel estimation.

Figure.5 compares the performance of channel estimation under linear type group delay with increscent coefficient. Combining with the phase variation curve shown in Figure.6 we can see that undoubtedly the larger coefficient cause more steep phase variation, consequently cause the worse performance of channel estimation .However ,when the coefficient vary in a certain range, the estimation of channel is nearly still not affected (as shown in Figure.4).

Figure.7 compares the performance of channel estimation under constant type group delay ($\tau = 0.026$), linear type group delay ($\tau = 0.026$), parabolic type group delay ($\tau = 0.011/3$) and asymmetric type group delay. In the figure, except for asymmetric type group delay, the former three type group delay obtain good and very close performance. The impact of group delay can be ignored. The square error of channel estimation of the parabolic type group delay is the smallest, i.e. the best performance because of the small coefficient. The asymmetric type group delay can approximate arbitrary practical group delay. In Figure.8 we can see that even the phase variation of asymmetric type group delay has been very large, the original performance of channel estimation is maintained and not suffer unrecoverable impact. In subsequent work, we can attempt to use more advanced channel estimation algorithm with high performance to validate that the performance of channel estimation will not affected as long as the coefficient vary in a certain range even asymmetric type group delay is used.

The performances of channel estimation and bit error rate for short-wave channel using different channel estimation algorithm are shown in Figure.9 and Figure.10 respectively. We can see from the figures that DFT interpolation

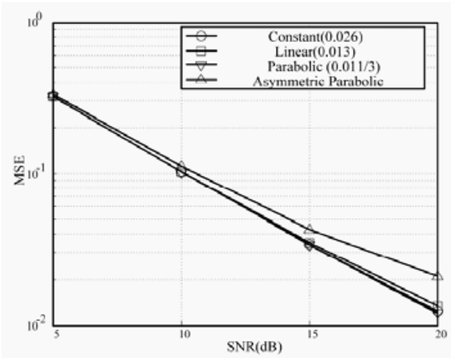


Figure 7 MSE performance of channel estimation under every type group delay.

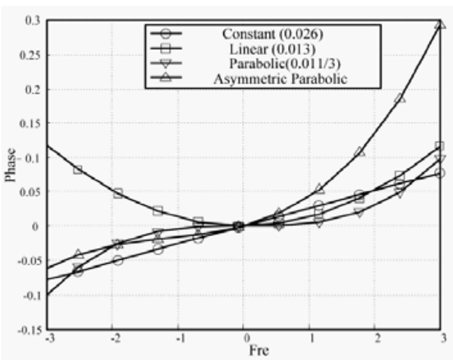


Figure 8 Phase variation curve of every type group delay.

algorithm is optimal, then cubic interpolation algorithm, then linear interpolation algorithm and constant interpolation algorithm is the worst. The conclusion is same with that in literature[21] and proves the universal adaptability of the channel estimation algorithm based on DFT used in this paper. From the performance comparison of bit error rate in Figure.10 we can get the conclusion, agreed well with the theoretical analysis, that the effect of group delay can be compensated by channel estimation as long as the group delay is not very severe.

5. Conclusions

In this paper, the performance of channel estimation in OFDM system was derived under a proposed simplified channel group delay model. It is shown that the present common theoretic analysis to verify the impact of group delay on OFDM system have deficiencies and are not sufficient enough to get the validity of the conclusion that group delay has impact on OFDM system and introduce ICI.

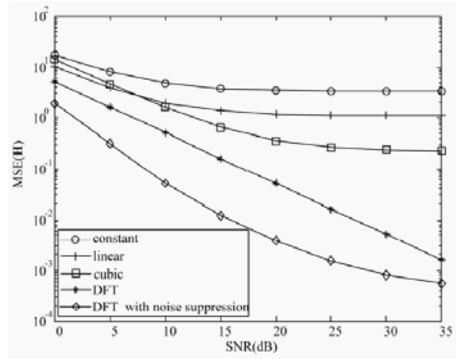


Figure 9 MSE performance of channel estimation using different traditional interpolation algorithm.

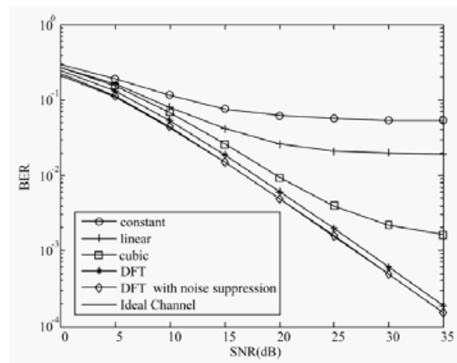


Figure 10 BER performance of channel estimation using different traditional interpolation algorithm.

Theoretic analysis and simulation results can validate that in OFDM system, whether group delay is linear, parabolic or asymmetric, when the coefficient vary in a certain range, group delay has limited impact on the performance of channel estimation.

When the group delay coefficients are too large, namely, phase vary sharply and has a high rate of change, group delay has obvious impact on OFDM system using simple rough channel estimation algorithm. However, the impact level of group delay using more advanced channel estimation algorithm is expected to be verified further.

Acknowledgement

This work was supported by the National Science Foundation of China under Grant number 61032002, 71001075, 71020107027and 61101090, Chinese Important National Science Technology Specific Projects under Grant 2011ZX03001-007-01, Program for New Century Excellent Talents in University, NCET-11-0058.

References

[1] N. Chen and G. T. Zhou. What is the price paid for superimposed training in OFDM, IEEE International Conference on Acoustics, Speech, and Signal Processing, May 17-21; Quebec, Canada. 421-424 (2004).
[2] J. E. Kleider, G. Maalouli and S. Gifford, et al. Preamble and embedded synchronization for RF carrier frequency-hopped OFDM, IEEE JSAC, 23, 920-931 (2005).
[3] L. J. Cimini. Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing, IEEE Trans. on Communications, 33, 665-675 (1985).
[4] B. Yang, B. L. Khaled B L and R. Cheng, et al. Channel estimation for OFDM transmission in multipath fading channels based on parametric channel modeling, IEEE Trans. on Communications, 49,467-479 (2001).
[5] G. HuDigital signal processing—theoryalgorithm and realization, Tsinghua university press, BeiJing (section 7.8) (2003).
[6] G. Tu, Rf circuit analysis and design, Beijing broadcasting institute publishing houseBeiJing, 97-102 (2003).
[7] M. Shuaib Khan and Robert King, Modified Inverse Weibull Distribution, Journal of Statistics Applications & Probability, 1, 115-132 (2012).
[8] C. C. Watterson. Experimental Confirmation of an HF Channel Model, IEEE Trans. Commun. Technol., COM-81, 792-803 (1970).
[9] J. D. Milson. Wideband Channel Characteristics and Short Spread-Spectrum Link, HF Radio Systems and Techniques Conference Publication, No.474 (2000).
[10] L. E. Vogler, J. A. Hoffmeyer. A model for wideband HF propagation channels, Radio Sci, 28, 1131-1142 (1993).
[11] J. F. Mastrangelo, J. L. Lemmon, L. E. Vogler, J. A. Hoffmeyer, L. E. Pratt, and C. J. Behm. A New Wideband High Frequency Channel Simulation System, IEEE Transactions on Communications, COM-45, 26-34 (1997).
[12] J. E. M. Nilsson, T. C. Gile. Wideband multi-carrier transmission for military HF communicationMILCOM 97,Nov 2-5, Monterey, CA, 2, 1046-1051 (1997).
[13] X. Zhu. The absolute group delay of the measurement system. Modern radar28,75-80 (2006).
[14] C. Gao and X. Cao. Effects of Group Delay on the Performance of OFDM System. ICISE2009, December 26-28; Nanjing, China, 2618-2621 (2009).
[15] H. Nyquist, Brand S. Measurement of phase distortion. BSTJ, 3, 523-526 (1930).
[16] L. HouB. Sun and X. Lu. Group delay characteristics of high-speed digital satellite relay system influence. Journal of measurement and control aircraft25, 55-57 (2006).
[17] Y. Li. Pilot-symbol-aided channel estimation for OFDM in wireless systems. IEEE Trans. on Vehicular Technology, 49, 1207-1215 (2000).

XIA LEI received her Ph.D. in the Department of Communication and Information Engineering from University of Electronic Science and Technology of China in 2005. Her major research interests are mobile communication, multicarrier techniques, cooperative wireless communications, etc. She has published about more than 40 journal and conference articles in referred journals and conferences. She has often worked as a technical reviewer for journals and conferences. She is an IEEE Member since 2004.

YAMIN SONG received bachelor's degree in communication engineering in 2010 at the University of Electronic Science and Technology of China(UESTC).He is studying a master's degree at UESTC from 2010 to the present.His research direction is the signal detection in communication systems.