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A Kalman Filtering Channel Estimation Method Based on State Transfer Coefficient Using Threshold Correction for UWB Systems

Shijie Zhang[1], Dan Wang[1] and Jun Zhao[2]
[1]*Information Engineering College, Henan University of Science and Technology, Luoyang 471023, China*
[2]*School of Management, Liaoning Institute of Science and Technology, Benxi 117004, China*
[1]*wangdaniel2004@163.com*

Abstract

Aimed at the divergence problem in the traditional Kalman Filtering (KF) channel estimation algorithm due to the inaccurate state transfer coefficient (STC), *this paper proposes a novel KF channel estimation method using the STC with threshold correction. By setting a reasonable threshold, the estimation performance of STC can be greatly improved in the time-varying Ultra-Wideband (UWB) channel environment. The simulation results demonstrate that, compared with the traditional estimation methods, the proposed channel estimation method can not only significantly improve the estimation performance but also effectively restrain the traditional KF's divergence problem.*

Keywords: *State transfer coefficient* (*STC*), *UWB, Kalman filtering*(*KF*), *Auto Regressive, Pilot, filter divergence*

1. Introduction

Presently, the UWB-OFDM technology has been one of the research hotspots in the communication fields due to the low power consumption, the high spectrum effectiveness and the high multipath resolution, *etc*. [1-2]. However, since the UWB wireless communication channel is extremely frequency selective, the transmitted signal can be impacted severely by the non-ideal channel. Moreover, the motion of transceiver or scattering object contributes to the Doppler frequency shift effect of channel. Therefore, the time-varying channel estimation problem is vital and difficult to be tackled for UWB wireless communications.

Recently, there are abundant research achievements about time-varying channel estimation problem in OFDM and UWB-OFDM systems. In [3], the authors analyzed the UWB-OFDM system performance in the quasi-static fading channels under the S-V indoor channel model. According to the time-varying fading characteristics of UWB channel, [4] set up a wide stationary unrelated scattering process and a Gaussian process with zero mean value, respectively. However, it does not give a specific implementation method. By analyzing the performance of UWB-OFDM system, [5] simulated the shift of scatter on the base of the time varying channel model and demonstrates that the scatter shift's impact on system performance can be ignored indoor. [6] Established the channel model with the Auto-Regressive process. And it conducted channel estimation through the lower dimension KF algorithm of pilot frequency, and put forward a combiner based on MMSE to amend KF. In [7], the authors introduced the improved KF equations, as well as analyzed the reasons of divergence and generation of filtering. Nevertheless, the methods above do not consider the time-varying fading issues occurred by the transceiver's shift in the UWB-OFDM systems. In other words, the channel estimation methods above cannot be directly applied into the time-varying UWB channel model.

This paper proposes a threshold correction method to modify the STC so as to restrain the divergence of KF algorithm in the time-varying UWB systems. Firstly, according to the time selectivity of UWB channel, the channel impulse response can be described as the AR model. Secondly, the KF algorithm is utilized based on pilots, where the LS algorithm is employed to get the STC estimate and the initial values of KF, and the STC value is refined by the threshold correction.

The paper is organized as follows. Section 2 describes the system model and channel model. In Section 3, the traditional KF algorithm is firstly introduced and then the KF method restraining the divergence by modifying the STC is presented. In Section 4, simulations are provided for proving the validness of the proposed method. Finally, a conclusion is drawn in Section 5.

2. System Description

2.1. UWB-OFDM System Model

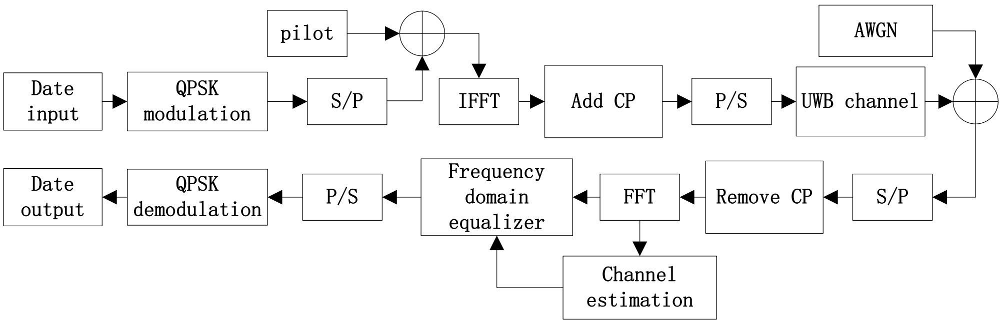

Figure 1. The UWB-OFDM System Model

Figure 1 describes the typical model of OFDM-UWB system [8]. In the transmitter, the frequency-domain symbol $X(i,k)$ is converted to the time-domain signal $x(i,n)$ via modulation, serial-to-parallel (S/P) conversion and inverse fast fourier transform (IFFT). Then, the UWB- OFDM signal of the ith symbol period can be indicated as:

$$\begin{aligned} x(i,n) &= \mathrm{IFFT}(X(i,k)) \\ &= \frac{1}{N}\sum_{k=0}^{N-1} X(i,k)\exp(\mathrm{j}2\pi nk/N) \end{aligned} \tag{1}$$

where N denotes the number of FFT sample points. The transformed data is added by the cyclic-prefix(CP), and then sent to the receiver through the fading channel. The receiver will finally get the received signal through a process opposite to the transmitter terminal. The received signal is expressed by

$$y(i,n) = \sum_{l=0}^{L-1} h_l(i,n)x(i,n-l) + w(i,n) \tag{2}$$

where L means the channel length, $h_l(i,n)$ stands for the channel impulse response, and $w(i,n)$ means the zero-mean Additive White Gaussian Noise(AWGN) with the variance of σ_w^2. The received signal in the frequency domain is represented as:

$$Y(i,k) = X(i,k)H(i,k) + W(i,k) \tag{3}$$

2.2. Channel Model

The UWB channel model is based on the cluster mode, so that there are more parameters and complicated simulation realizations [9]. The AR model is extensively used because of its simple parameter and easy simulation realization. As for the transceiver shift, the channel can be modeled as a wide stationary uncorrelated scattering process. In this way, the channel impulse response can be described as the AR model of order P. And the time varying channel model can be depicted by

$$h(i,n) = \sum_{k=1}^{P} \alpha(k) h(i-k,n) + v(i) \tag{4}$$

where $v(i)$ is the zero-mean AWGN with the variance of σ_v^2 . $a(k)$ indicates the STC of channel decided by Doppler frequency offset $f_d T_s$. For convenience, the AR model of order one is employed in this paper. By the Yule-Walker equations available, we have

$$a = J_0^2(2\pi f_d T_s) \tag{5}$$

$$\sigma_v^2 = 1 - J_0^2(2\pi f_d T_s) \tag{6}$$

where J_0 is first-order Bessel function, f_d is Doppler shift, T_S is Information symbol cycle.

3. Channel Estimation

3.1. The Traditional KF Channel Estimation Method

The KF method is a real time recursive algorithm of dealing with the random signal, which is the optimal estimation method based on the minimum mean square error. It adopts the state space model of signal and noise and the estimates of state variables are updated by the estimation of the previous value and the current measurement value. Therefore, the KF method can be divided into two parts: the time status update equation and the measurement update equation. The time status update equation can be regarded as the prediction equation, the measurement update equation can be regarded as the correction equation which carries out recursion in the order of prediction-actual measurement-correction. Then, the measured value is used to eliminate the random interference and update the system state. The KF channel estimation method can be described as follows [10].

$$G(i) = \alpha(i) K(i,i\text{-}1) s^H(i)[s(i) K(i,i\text{-}1) s^H(i) + \sigma_w^2]^{-1} \tag{7}$$

$$e(i) = y(i) - s(i)\hat{h}(i) \tag{8}$$

$$\hat{h}(i+1) = \alpha(i)\hat{h}(i) + G(i)e(i) \tag{9}$$

$$P(i) = [1 - \alpha^{-1}(i) G(i) s(i)] K(i) \tag{10}$$

$$K(i+1) = \alpha(i) P(i) \alpha^H(i) + \sigma_v^2 \tag{11}$$

where $G(i)$ is the KF gain, $e(i)$ is the evaluated error, $\hat{h}(i)$ is the revised channel estimate of one-step prediction, $P(i)$ is the steady state covariance of the revised channel estimate, and $s(i)$ is estimated transmitted information. This method needs the known initial estimation value $\hat{h}(0)$, the channel transfer coefficient $a(i)$, the observed value $y(i)$, the estimated transmitted information *s*(*i*) and the process noise variance σ_v^2 and the observation noise variance σ_w^2. However, these parameters are unknown except for the observed value *y*(*i*). Therefore, these parameters need to be estimated in advance. Herein, the KF channel estimation is conducted based on the comb pilots due to the time-varying channel, which is described as follows.

Step1) to estimate the initial values $\hat{h}(0)$. Firstly, the channel frequency responses (CFRs) at the pilot tones are obtained by the least square (LS) estimation. Secondly, the overall channel frequency responses (CFRs) are computed by FFT interpolation on the CFRs at the pilot tones.

Step2) iterations: to estimate the channel STC *a*(*i*) as a rule of LS, *i.e.*,

$$\hat{\alpha}(i) = \hat{h}^p(i+1) \big/ \hat{h}^p(i), i = 0,1\cdots, N_{ofdm} - 1 \tag{12}$$

Step3) to calculate the process noise variance $\hat{\sigma}_v^2 = 1 - \hat{\alpha}^2(i)$ and the observation noise variance $\hat{\sigma}_w^2 = E[\hat{W}\hat{W}^H]$ by the Yule-Walker equation, where $\hat{W} = \hat{h}^p(i) - h^p(i)$.

Step4) repeat steps of 2 and 3 until $i = N_{ofdm} - 1$.

3.2. The Proposed KF Algorithm of Restraining Divergence

Under the ideal conditions, the KF method is linear unbiased minimum variance estimation. However, the state estimation is practically biased. The variance of evaluated error is probably large, and even much larger than the scope of the theoretical variance. This phenomenon is called as the filter divergence in filtering theory and could make the KF method invalid. Filter's divergence could be caused by many reasons, such as the inaccurate mathematical model, which cannot reflect the actual physical process and the inaccurate STC influenced by the system noise.

Due to the existence of noise, the time-varying channel cannot be tracked very well only by pilots so that the estimation error of STC is too large. When the signal to noise ratio (SNR) is small, the error will be so large that they will seriously affect the filtering effect and make the filter seriously diverge. In order to overcome this drawback, the paper will modify the initially estimated STC by a threshold revision and take the approaching corrections for the STC which do not meet the threshold requirements. Thus, the proposed method will suppress the harmful effect caused by the STC estimation deviation. The proposed threshold correction method of STC is given as follows:

Firstly, we set the threshold range to amend the initial STC estimated by pilots as

$$\hat{\alpha}(i) \in [\lambda_{\min}, \lambda_{\max}] \qquad i = 0,1\cdots, N_{ofdm} - 1 \tag{13}$$

where $\lambda_{\min}$ is the lower bound of threshold, and $\lambda_{\max}$ is the upper bound of threshold. The threshold value should be determined to make the STC corresponding to the ideal value.

Secondly, the STC (13) meeting the threshold requirement is numerically averaged and, the mean value can be computed by

$$\bar{\alpha} = mean\left(\sum_{i=0}^{N_{ofdm}-1} \hat{\alpha}(i)\right) \tag{14}$$

Thus, the averaged STC is more close to the theoretical value and will be infinitely close to the ideal value in case of weak noise and small Doppler shift. Hence, the divergence of filter can be effectively restrained.

Finally, in order to further reduce the influence of STC estimation deviation on the system, the averaged STC needs to be reset by

$$\hat{\alpha}(i) = \beta\hat{\alpha}(i) + (1-\beta)\bar{\alpha} \tag{15}$$

where β is defined as the tune coefficient, *i.e.*,

$$\beta = \begin{cases} 1\cdots \ for \quad \hat{\alpha}(i) \in [\lambda_{\min}, \lambda_{\max}] \\ 0\cdots \ otherwise \end{cases} \tag{16}$$

If the STC $\alpha(i)$ is beyond the threshold scope, it should be corrected to approach $\bar{\alpha}$. The proposed KF method restraining divergence is shown in Figure 2.

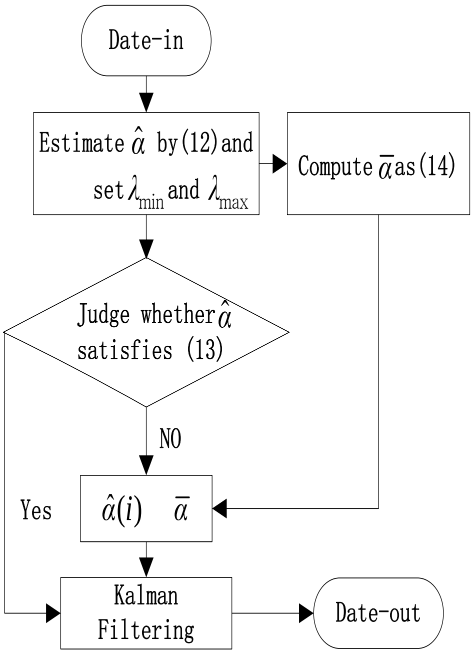

Figure 2. Flowchart of the Proposed KF Method Restraining Divergence

4. Simulation Results

In this section, we numerically study the performance of our proposed channel estimation method as well as the traditional methods under the UWB-OFDM system model above. The MATLAB tool is used for simulating the 0~4m LOS (CM1) channel environment. The specific system parameters are described in Table 1.

Table 1. System Parameters

Parameters	Values
Bandwidth of system（B）	3.1-4.8GHz
Bandwidth of subbands（ΔB）	528MHz
Number of FFT sample point（N）	512
Number of CP（N_{CP}）	128
Number of OFDM symbol（N_{ofdm}）	128
Number of Pilot interval	8
Modulation method	QPSK
Movement speed of transceiver（V）	30、60、120（km/h)
threshold λ	0.9～1.1

Figure 3 shows the comparison among the proposed estimation method, the traditional KF method, the LS channel estimation method, the FFT interpolation scheme and the ideal KF method, respectively. In the ideal KF method, used is the known channel state transfer coefficient. It can be seen that the traditional KF method has the worst estimation performance and when the SNR is less than 15dB, is even worse than the LS channel estimation. Its estimation performance gradually becomes better with the increase of SNR. This is mainly because the estimated channel STC is affected by noise seriously. The proposed estimation method significantly outperforms the traditional methods and approaches the performance of ideal KF method very closely in the whole SNR range.

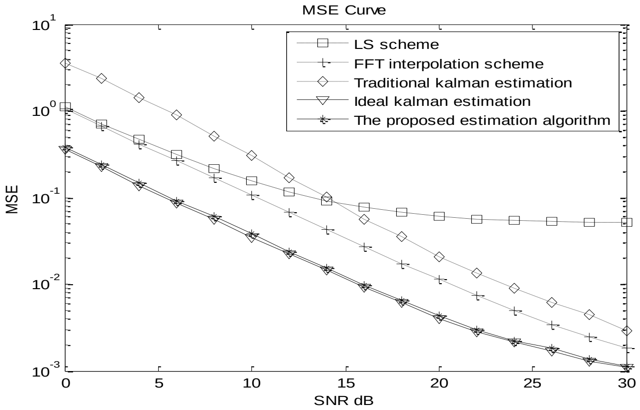

Figure 3. MSE vs. SNR Curve over Channel with v=30km/h

In Figure 4 and Figure 5, the mobile station’s speed is increased to 60km/h and 120km/h, respectively. Results indicate that, despite of the higher speed level, the proposed method still has a better estimation performance than the traditional estimation methods. Moreover, with the faster moving speed, this superiority will become more and more apparent. In Figure 4, the proposed method's MSE value is decreased by approximately one order of magnitude than traditional estimation methods, and by approximately two orders of magnitude in Figure 5. The traditional methods perform worse due to the time-varying channel, whereas the proposed method is still so effective to estimate the STC, as to maintain the KF’s ability of tracking the time-varying channel fastly.

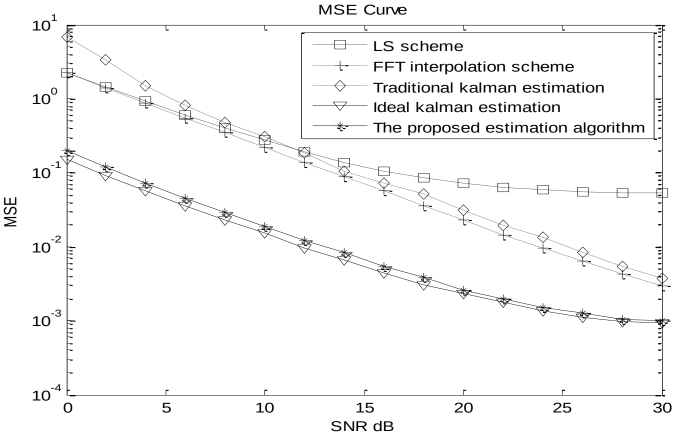

Figure 4. MSE vs. SNR curve over Channel with v=60km/h

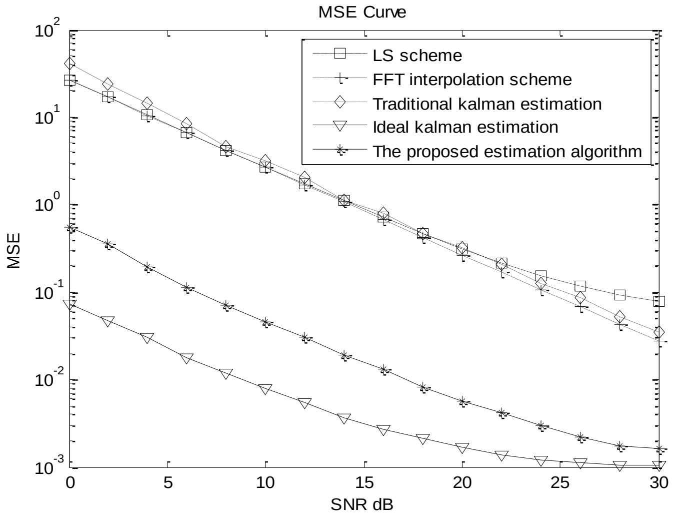

Figure 5. MSE vs. SNR Curve over Channel with v=120km/h

5. Conclusion

This paper proposed a KF algorithm which can effectively restrain the filter divergence caused by the inaccurate channel STC estimate. Based on the comb-type pilots, the proposed method firstly estimates the initial KF estimation values and computes the STC estimate of LS. Then, the STC estimate is statistically averaged and is refined by threshold correction. Therefore, the time-varying channel can be tracked effectively since the divergence of KF method can be avoided validly. Theoretical analyses and simulation experiments show that the proposed algorithm can not only achieve simple implementation, but also effectively improve the channel estimation performance.

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Authors

Shijie Zhang is now a graduate student in Henan University of Science and Technology. His research concerns wireless communications and time-varying channel estimation on UWB system.

Dan Wang was born in Liaoning province, China, in 1979. She received her B.S. and M.S. degrees from Jilin University, P.R. China, in 2001 and 2004, respectively. She received her Ph. D degree in the Department of Electronic Engineering, Shanghai Jiao Tong University, China, in 2009. Currently, she is an associate professor with the Electronic Information Engineering College, Henan University of Science and Technology, Luoyang, P. R. China. Her current research interests in the area of wireless communication and signal processing including mobile WiMAX, OFDM and ultra-wideband wireless communication systems, etc.

Jun ZHAO was born in Benxi, Liaoning province, China, in 1963. She received the B.S. degree from Benxi University, China, in 1985, and the M.S. degree from Northeast University, China, in 2006, respectively. She is currently a professor at Liaoning Institute of Science and Technology, China. Her research concerns signal analysis and processing, and information management.