Weighted Coefficient-Based Quadratic Fast Time-Varying Channel Estimation Algorithm for ICI Cancellation Postprint

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Abstract

A two-stage fast time-varying channel estimation algorithm incorporating weighting coefficients for inter-carrier interference (ICI) elimination is proposed for high-mobility environments, where ICI is induced by Doppler shift. The algorithm performs channel estimation in two stages: the first stage provides channel state information and eliminates ICI while maintaining the symbol rate, and the second stage, conducted under ICI-free conditions, enhances channel estimation accuracy. Furthermore, the simplified parallel interference cancellation (PIC) algorithm is improved by introducing weighting coefficients based on the minimum mean square error (MMSE) criterion to minimize the residual error after ICI elimination. Simulation results and theoretical analysis exhibit excellent consistency. When the channel signal-to-noise ratio is 0 dB, the normalized mean square error (NMSE) performance gain reaches approximately 0.0714, thereby improving the precision of fast time-varying channel estimation.

Full Text

Twice Rapidly Time-Varying Channel Estimation Algorithm Based on ICI Cancellation Using Weighted Coefficient

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Abstract: This paper proposes a twice channel estimation algorithm that introduces a weighted coefficient to cancel inter-carrier interference (ICI) caused by Doppler frequency shift in high-speed mobile environments. The algorithm performs channel estimation in two stages: the first estimation provides channel state information to cancel ICI while ensuring symbol rate, and the second estimation, conducted under ICI-free conditions, improves channel estimation accuracy. The algorithm also improves upon the simplified parallel interference cancellation (PIC) algorithm by introducing a weighted coefficient based on the minimum mean square error (MMSE) criterion to minimize residual error after ICI cancellation. Simulation results show good agreement with theoretical analysis. When the channel SNR is 0 dB, the normalized mean square error (NMSE) performance gain reaches approximately 0.0714, demonstrating improved accuracy for rapidly time-varying channel estimation.

Keywords: weighted coefficient; ICI cancellation; twice estimate; rapidly time-varying channel; PIC algorithm

0 Introduction

With the rapid development of high-speed railways, railway communication systems face numerous challenges. In high-mobility environments, the number of parameters to be estimated for rapidly time-varying channels increases dramatically, necessitating channel models that reduce the number of unknowns to accurately represent the true channel behavior. Common time-varying channel fitting methods include the linear time-varying (LTV) model and basis expansion model (BEM). As the optimal model for time-frequency doubly-selective channels, BEM has attracted widespread attention in recent years. Methods using BEM for rapidly time-varying channel estimation require fewer pilots and offer good performance, but they do not consider ICI effects, resulting in limited accuracy improvement under large Doppler frequency shifts.

ICI mitigation is crucial for improving rapidly time-varying channel estimation accuracy. Reference [8] combines a simplified PIC scheme with decision statistics to eliminate ICI and reduce data symbol detection error rates. Reference [9] proposes a novel PIC algorithm that cancels ICI in each iteration before equalization, improving both channel estimation and equalization performance. However, these algorithms address ICI impact in isolation without verifying the improvement in channel estimation after ICI cancellation. Reference [10] integrates ICI cancellation with channel estimation, designing a receiver structure comprising three main modules: channel estimation, adaptive channel parameter extraction, and PIC. It uses estimated channel gains to estimate ICI gains and then combines them with detected signals to cancel ICI. Real-world tests on Taiwan’ s high-speed rail demonstrate performance improvements of 2–8 dB at 30 dB SNR. However, the iterative PIC approach for ICI cancellation suffers from error propagation and convergence difficulties. Reference [11] proposes a three-step MMSE-based iterative ICI cancellation algorithm including MMSE channel estimation, MMSE equalization, and ICI cancellation, which significantly reduces system BER but entails high computational complexity.

To address these issues, this paper proposes a twice rapidly time-varying channel estimation algorithm based on ICI cancellation using a weighted coefficient. The algorithm uses the frequency-domain channel matrix obtained from the first estimation combined with detected signals to derive ICI interference terms. It then employs an improved simplified PIC algorithm to cancel ICI. Since no iterative method is used to approximate the true value, residual errors cannot be ignored. Therefore, we improve the simplified PIC algorithm by introducing a weighted coefficient based on the MMSE criterion to minimize residual error after ICI cancellation. Finally, the algorithm performs a second channel estimation using the ICI-cancelled received signal, comprehensively considering the mutual influence between ICI cancellation and channel estimation to improve accuracy.

1 Twice Rapidly Time-Varying Channel Estimation Algorithm Based on ICI Cancellation

1.1 Algorithm Process

As shown in [Figure 1: see original paper], the proposed twice rapidly time-varying channel estimation algorithm proceeds as follows: First, BEM is used to model the rapidly time-varying channel and obtain the estimation matrix $\mathbf{F}_{\mathrm{LMMSE}}$. The first channel estimation is then performed to obtain the frequency-domain channel matrix $\hat{\mathbf{H}}$. An improved simplified PIC algorithm cancels ICI to obtain the ICI-cancelled frequency-domain received signal $\mathbf{Y}_{2nd}$. Finally, a second channel estimation using $\mathbf{Y}_{2nd}$ yields $\hat{\mathbf{H}}_{2nd}$, completing the channel estimation. This approach eliminates the impact of ICI on rapidly time-varying channel estimation and further improves accuracy.

1.1.1 Channel Model Establishment Common BEMs include Complex Exponential BEM (CE-BEM), Generalized CE-BEM (GCE-BEM), Polynomial BEM (P-BEM), Discrete Prolate Spheroidal Sequence BEM (DPS-BEM), and Discrete Karhunen-Loeve BEM (DKL-BEM). Among these, DKL-BEM is optimal under the MMSE criterion. This paper adopts DKL-BEM for channel modeling.

Using DKL-BEM to describe doubly-selective channels, when the maximum delay is $\tau_{\max}$ and the maximum Doppler frequency shift is $f_{\max}$, the channel can be modeled as an FIR filter where each tap is represented as a superposition of basis functions. The time-domain channel response can be expressed as:

$$h_l(n) = \sum_{q=0}^{Q-1} b_q(n) g_{l,q}$$

where $b_q(n)$ represents the DKL-BEM basis functions at time n, and $g_{l,q}$ represents the DKL-BEM basis coefficients, which remain constant within one OFDM symbol period.

After transmission through an AWGN channel, the received frequency-domain signal at the receiver can be expressed as [6]:

$$\mathbf{Y} = \mathbf{H}_{\text{ave}}\mathbf{X} + \mathbf{H}_{\text{ICI}}\mathbf{X} + \mathbf{W}$$

where $\mathbf{X}$ and $\mathbf{Y}$ are the transmitted and received frequency-domain signals, respectively; $\mathbf{W}$ is the frequency-domain representation of time-domain AWGN; $\mathbf{H}_{\text{ave}}$ is the $N \times N$ channel frequency-domain matrix with diagonal elements $H(k,k)$; and $\mathbf{H}_{\text{ICI}}$ is the $N \times N$ interference matrix from data subcarriers to pilot subcarriers with zero diagonal elements and non-diagonal elements $H(k,v)$ for $k \neq v$. Analysis of this equation reveals that when $h_l(n)$ varies with time n, $\mathbf{H}$ has non-diagonal elements, indicating the presence of ICI in rapidly time-varying channels. Therefore, ICI interference must be canceled to improve estimation accuracy.

1.1.2 Channel Estimation Matrix **1) Pilot Structure** This paper employs the common frequency-domain comb pilot structure (FDKD) for channel estimation. Assuming M pilot clusters in one OFDM symbol, each cluster contains a non-zero pilots with b zero pilots on each side. The M pilot clusters are periodically inserted into one OFDM symbol, with each pilot cluster vector denoted as $\mathbf{x}_m^P$, where P_m is the starting position of the m-th pilot cluster. An OFDM symbol can be divided into two parts: $\mathbf{X}_P$ for all pilot symbols and $\mathbf{X}_d$ for the remaining data symbols. The pilot structure is shown in [Figure 2: see original paper].

2) Channel Estimation Method BEM characterizes the channel using time-varying basis functions and time-invariant basis coefficients, converting channel estimation into a linear parameter (basis coefficient) estimation problem. However, obtaining the basis coefficients requires first determining the estimation matrix. Common estimation methods include Least Squares (LS) and Linear Minimum Mean Square Error (LMMSE). While LS has low complexity, it does not account for ICI and noise interference, yielding unsatisfactory results under large Doppler frequency shifts or low SNR. LMMSE, though more complex due to its dependence on channel information and autocorrelation matrix calculations, offers higher accuracy by comprehensively considering ICI, noise, and multipath delay effects. Therefore, this paper adopts LMMSE for basis coefficient estimation, finding an estimation matrix $\mathbf{F}_{\text{LMMSE}}$ that minimizes the MSE between the actual and estimated basis coefficients:

$$\mathbf{F}_{\text{LMMSE}} = \mathbf{R}_{gg}\mathbf{D}^H(\mathbf{D}\mathbf{R}_{gg}\mathbf{D}^H + \mathbf{R}_{\text{ICI}} + \mathbf{R}_w)^{-1}$$

where $\mathbf{R}_{gg}$, $\mathbf{R}_{\text{ICI}}$, and $\mathbf{R}_w$ are the autocorrelation matrices of the BEM basis coefficient vector, ICI interference term, and noise, respectively.

1.1.3 First Channel Estimation Using the estimation matrix from Section 1.1.2, the basis coefficients can be estimated as:

$$\hat{\mathbf{g}} = \mathbf{F}_{\mathrm{LMMSE}}\mathbf{Y}_P$$

where $\mathbf{Y}_P$ corresponds to the frequency-domain received data at all pilot subcarriers. After obtaining the basis coefficients, the time-domain channel response is derived using Equation (1), and the frequency-domain channel matrix is obtained using Equation (3).

1.1.4 ICI Cancellation Method From Equation (2), when the channel varies approximately linearly, ICI can be treated as additive interference. Reference [18] employs an MMSE-based equalizer where the detection signal can be expressed as:

$$\hat{\mathbf{X}} = \mathbf{G}\mathbf{Y}$$

Using the simplified PIC algorithm to cancel ICI, the frequency-domain received signal after ICI cancellation becomes:

$$\mathbf{Y}_{2nd} = \mathbf{Y} - \hat{\mathbf{H}}_{\mathrm{ICI}}\hat{\mathbf{X}}$$

where $\hat{\mathbf{H}}_{\mathrm{ICI}} = \mathrm{diag}(\mathrm{diag}(\hat{\mathbf{H}})) - \hat{\mathbf{H}}$ is a diagonal matrix formed from the diagonal elements of $\hat{\mathbf{H}}$.

1.1.5 Second Channel Estimation The second channel estimation uses $\mathbf{Y}_{2nd}$ to estimate the basis coefficients:

$$\hat{\mathbf{g}}_{2nd} = \mathbf{F}_{\mathrm{LMMSE}}\mathbf{Y}_{2nd,P}$$

where $\mathbf{Y}_{2nd,P}$ corresponds to the ICI-cancelled frequency-domain received data at all pilot subcarriers. After obtaining the coefficients, the frequency-domain channel matrix $\hat{\mathbf{H}}_{2nd}$ is derived using the same method as in Section 1.1.3.

1.2 Algorithm Simulation and Analysis

Using MATLAB simulation platform at a speed of 350 km/h, this section compares the performance of the conventional DKL-BEM algorithm with the proposed ICI-cancellation-based twice rapidly time-varying channel estimation algorithm, as shown in [Figure 3: see original paper], to verify correctness and effectiveness. Normalized Mean Square Error (NMSE) is defined to measure channel estimation performance:

$$\mathrm{NMSE} = \frac{\sum_{l=0}^{L-1}\sum_{n=0}^{N-1} E\{|h_l(n) - \hat{h}_l(n)|^2\}}{\sum_{l=0}^{L-1}\sum_{n=0}^{N-1} E\{|h_l(n)|^2\}}$$

where $h_l(n)$ represents the actual channel tap response generated by the Jakes model. The simulation uses a carrier frequency of $f_c = 2$ GHz and 20 OFDM symbols per frame. Detailed parameters are listed in .

As shown in [Figure 3: see original paper], when SNR > 14.3 dB, the proposed algorithm' s performance degrades compared to the conventional DKL-LMMSE algorithm, indicating that the twice estimation approach is more suitable for lower SNR scenarios. The consistency between theoretical analysis and simulation results validates the algorithm' s correctness and effectiveness.

2 Weighted Coefficient Analysis

2.1 Introduction of Weighted Coefficient

To further analyze the ICI cancellation in Equation (14), the transmitted data is divided into pilot part $\mathbf{X}_P$ and data part $\mathbf{X}_d$. Equation (14) can be expressed as [19]:

$$\mathbf{Y} = \mathbf{A}_s \mathrm{diag}(\mathbf{X}_P)\mathbf{Fg} + \mathbf{A}_d \mathrm{diag}(\mathbf{X}_d)\mathbf{Fg} + \mathbf{W}$$

Substituting into Equation (14), the ICI-cancelled frequency-domain received signal becomes:

$$\mathbf{Y}_{2nd} = \mathbf{A}_s \mathrm{diag}(\mathbf{X}_P)\mathbf{Fg} + \mathbf{A}_d \mathrm{diag}(\mathbf{X}_d)\mathbf{Fg} - \mu \mathbf{A}_d \mathrm{diag}(\hat{\mathbf{c}})\mathbf{g} + \mathbf{W}$$

where $\hat{\mathbf{c}}$ represents the ICI interference term obtained from the first channel estimation. The second term on the right-hand side represents the residual error from interference cancellation. Smaller residual error yields better ICI cancellation. Traditional PIC algorithms use iterative methods to reduce residual error but suffer from error propagation and convergence issues. This paper introduces a weighted coefficient based on the MMSE criterion to reduce residual error:

$$\mathbf{Y}_{2nd} = \mathbf{A}_s \mathrm{diag}(\mathbf{X}_P)\mathbf{Fg} + \mathbf{A}_d \mathrm{diag}(\mathbf{X}_d)\mathbf{Fg} - \mu \mathbf{A}_d \mathrm{diag}(\hat{\mathbf{c}})\mathbf{g} + \mathbf{W}$$

The weighted coefficient is selected according to:

$$\mu = \arg\min_{\mu} E\{\|\mathbf{g} - \hat{\mathbf{g}}\|^2\}$$

The ICI cancellation process with weighted coefficient is illustrated in [Figure 4: see original paper]. Since ICI' s impact on channel estimation is reduced after cancellation, the second channel estimation using $\mathbf{Y}_{2nd}$ improves accuracy.

2.2 Algorithm Simulation and Analysis

Using the same simulation environment as Section 1.2, the weighted coefficient module in [Figure 4: see original paper] provides appropriate values based on current mobility speed and SNR according to the minimum MSE criterion. When speed and SNR change, the optimal value changes accordingly. For example, at v = 350 km/h and SNR = 15 dB, the optimal is 0.4, obtained through parameter extraction from simulation software.

[Figure 5: see original paper] shows NMSE versus weighted coefficient , demonstrating that = 0.4 provides maximum performance gain over conventional DKL-LMMSE. [Figure 6: see original paper] further validates the optimal value, showing that = 0.4 outperforms = 0.2 and = 0.6, consistent with theoretical analysis.

As shown in [Figure 7: see original paper], after introducing the weighted coefficient, the impact of residual error on channel estimation is significantly reduced. Although = 0.4 is optimal for SNR = 15 dB, the proposed algorithm outperforms conventional DKL-LMMSE across SNR = 0–20 dB, achieving maximum NMSE performance gain of 0.0714 at SNR = 0 dB, as summarized in .

3 Conclusion

This paper first proposes a twice rapidly time-varying channel estimation algorithm based on ICI cancellation. The algorithm employs two-stage estimation: the first provides channel state information for ICI cancellation while maintaining symbol rate, and the second improves estimation accuracy under ICI-free conditions. However, research shows that beyond a certain SNR threshold, the twice estimation approach underperforms conventional algorithms. Therefore, we improve the simplified PIC algorithm by introducing weighted coefficient to reduce residual error impact. Simulation results demonstrate that the proposed algorithm achieves noticeable performance improvement across SNR = 0–20 dB, with maximum NMSE gain of 0.0714 at SNR = 0 dB.

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Note: Figure translations are in progress. See original paper for figures.