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Time-varying channel estimation through optimal piece-wise time-invariant approximation for high-speed train wireless communications

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A B S T R A C T

The practical time-varying channel between a high-speed train (HST) and infrastructure has a single Doppler shift on each resolvable multipath in most cases. As a result, the HST channel can be modelled by only $2L$ parameters: L Doppler shifts and L complex channel gains. Based on this observation, we propose a novel channel estimation technique for orthogonal frequency-division multiplexing (OFDM) systems running on a HST, with the name PIece-wise Time-Invariant Approximation (PITIA). In PITIA, the HST channel is approximated by a bunch of time-invariant channels, whose channel impulse responses (CIRs) can be estimated through pilots. Variations of these CIR samples over time derive both Doppler shifts and complex channel gains, so the whole time-varying channel can be reconstructed. PITIA enjoys low computation complexity of $\mathcal{O}(NL)$ for N subcarriers. The optimal duration of time-invariant channels used to approximate HST channel is derived from both analytical analysis and simulations. Compared to basis expansion model (BEM) methods, PITIA uses fewer channel parameters with comparable modelling error, shows better normalized mean squared error (NMSE) performance under high-mobility and high signal-to-noise ratio (SNR) environments, and achieves comparable NMSE in low SNR regime.

1. Introduction

With the rapid deployment of high-speed trains (HSTs) around the world and development of intelligent transportation systems, providing broadband wireless communications between a HST and infrastructure is becoming indispensable to support various attractive services, such as Internet access, on-board data services, and multimedia advertisements, etc. [1,2]. Most prospective solutions for the broadband communication are Long Term Evolution (LTE) [3] and Worldwide Interoperability for Microwave Access (WiMax) [4], which adopt orthogonal frequency-division multiplexing (OFDM) due to its immunity to multipath, especially when the communication range is long. However, the high-mobility feature of HST results in time-varying channel which introduces significant challenges on channel estimation and complicates the design of channel estimator, whose performance is critical to OFDM receiver.

For an OFDM system, the channel is considered as time-varying when Doppler spread is comparable to subcarrier spacing. As an example, in LTE system which will be equipped on HST in many countries [5,6], subcarrier spacing is 15 kHz while Doppler spread can be 0.84 kHz when the travelling speed of HST is 350 km/h; therefore, the HST channel is considered as time-varying for LTE. It is well-known that, time-varying channel introduces inter-carrier-interference (ICI) to OFDM systems and increases the noise floor if a traditional single-tap channel equalizer is adopted [7].

A time-varying channel features much more parameters than those of a time-invariant channel. When an OFDM system with N subcarriers runs in a time-varying channel with L taps (L resolvable multipath components), the general time-varying channel model $h(t,\tau)$ for each OFDM symbol contains NL unknown parameters, much more than the observations at the receiver (at most $N+L$ observations for each OFDM symbol). Therefore, the key point in time-varying channel estimation (TVCE) is to approximate $h(t,\tau)$ with a simplified and realistic model that contains a

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reduced number (compared to NL) of parameters, so that a practical way to estimate all these parameters can be found.

As an advanced channel modelling method, basis expansion model (BEM) draws much attentions in recent years [8–22]. It approximates each channel tap by a set of basis functions, then TVCE is equivalent to estimating a few BEM coefficients. Existing BEM based algorithms (called BEM methods throughout the paper) are based on either general time-varying channel model [8–10] or preknown channel statistics [11]. Although the general time-varying channel model fits all kinds of environments including HST channel, it is less accurate and requires more channel parameters (or BEM coefficients) to be estimated than the ones based on preknown channel statistics or Doppler spectrum. However, if an algorithm requires preknown Doppler spectrum, the number of BEM coefficients may be reduced, but its modelling error increases significantly if there exists mismatch between the assumed Doppler spectrum and real situation.

Reducing the number of channel parameters is very important, because in a linear system with fixed number of observations, fewer parameters to be estimated lead to better anti-noise ability [23]. However, doing this is also risky, since the modelling error may grow and the noise floor may rise. To address this issue, we use the specific channel statistics of HST to reduce the number of channel parameters, which are then estimated by a novel algorithm.

HST channel has an important feature that, in most cases there exists only one Doppler shift on each resolvable multipath, although Doppler shifts on different multipath components may differ from each other and follow a certain distribution. The reasons are twofold. Firstly, the HST system operates in rural or open channels with line-of-sight (LOS) propagation and limited number of multipath components in most cases; therefore, there is very little chance that multiple multipath components fall into the same channel tap. Secondly, in case that some multipath components collide with each other, there is a great chance that they come from the reflectors located close to each other and suffer from similar Doppler shifts.

This feature is validated by WINNER II channel model [24] (with HST scenario), which is an empirical channel model derived from extensive channel measurement campaigns, and is widely adopted in researches about LTE and WiMAX [25–27]. As a result, the HST channel can be modelled by $2L$ parameters: L Doppler shifts and L complex channel gains.

Motivated by the above finding and the necessity to reduce the number of channel parameters, we propose a novel TVCE algorithm based on this simplified channel model for HST wireless communications. To solve the non-linear estimation problem introduced by Doppler shifts, we approximate the simplified channel model by a bunch of time-invariant channels, whose channel impulse responses (CIRs) can be estimated through pilots; we name this technique as PIece-wise Time-Invariant Approximation (PITIA). Then variations of these CIR samples derive both Doppler shifts and complex channel gains for all channel taps, and $h(t,\tau)$ is reconstructed accordingly.

The proposed algorithm enjoys low computation complexity, which is around $\mathcal{O}(NL)$ for N subcarriers. In other words, it has similar complexity as fast Fourier transform (FFT) operation, and is affordable for most OFDM receivers.

We provide extensive performance analysis in the paper. It is found that performances of both BEM methods and proposed HST channel estimation algorithm are determined by two factors: modelling error and anti-noise ability. For BEM methods, more basis functions lead to smaller modelling error and worse anti-noise ability (due to larger number of BEM coefficients to be estimated). For the proposed algorithm, the two factors are affected by a design parameter K_1, which determines the duration of time-invariant channels used to approximate a HST channel. Larger K_1 leads to more modelling error; if $K_1 = N/L$, the proposed algorithm degrades to conventional single-tap channel equalizer. In practice, K_1 is set to a small value in order to reduce modelling error, and we derive the optimal value of K_1 through both theoretical study and simulations.

Simulation results show that, to achieve acceptable modelling error, the proposed algorithm requires fewer channel parameters compared to BEM methods. With the simplified channel model for HST, BEM methods still need at least $3L$ channel parameters in order to keep the modelling error smaller than 1E–6 [19], because the number of basis functions is determined by maximum Doppler shift rather than the number of Doppler shifts on each multipath. On the other hand, the proposed algorithm only needs $2L$ channel parameters no matter how large Doppler shift is, while the modelling error is around 1E-6. In other words, the proposed algorithm benefits from the specific feature of HST channel, while BEM methods do not.

We use normalized mean squared error (NMSE) to evaluate the proposed algorithm's performance, and derive its analytical value and numerical results. We compare our algorithm with BEM methods that adopt least squares (LS) estimator [13], since both types of methods have similar computation complexity. It is shown that the proposed algorithm outperforms BEM methods in high mobility and high signal-to-noise ratio (SNR) environments and achieves comparable performance in low SNR regime.

Although the proposed algorithm is designed for HST channel, it is suitable for other applications with the following three channel characteristics: small delay spread, large Doppler spread, and sparse multipath. Typical examples include satellite communications [28] and air-ground communications for unmanned aircraft systems [29]. Satellite communications can also offer high-speed Internet access to HST, but currently not widely used due to their high expense.

We summarize the related works in Section 2, and provide system model together with a simplified channel model in Section 3. The proposed TVCE algorithm is introduced in Section 4 and evaluated in Section 5. Finally, the whole paper is concluded in Section 6. Throughout the paper, $(\cdot)^H$ represents complex conjugate transpose, $E\{\cdot\}$ stands for expected value, and $\mathbf{I}_N$ denotes the $N \times N$ identity matrix.

2. Related work

OFDM systems exposed to time-varying channels suffer from inter-carrier interference (ICI), which is the cause of noise floor and calls for advanced remedies. In early works, ICI's are cancelled by diversity over subcarriers [30,31] and estimated by grouped pilots on continuous subcarriers [32,33]. In these works, the traditional single-tap channel equalizer is upgraded to multi-tap equalizers, with the penalty of high computation complexity or low spectrum efficiency.

Recent works in time-varying channel estimation (TVCE) model the time-varying channel as $h(t,\tau)$ where t and τ denote time and channel dispersion, respectively. Some algorithms focus on the estimation of $h(t,\tau)$ [8–22], while others are devoted to designing low-complexity channel equalizers when $h(t,\tau)$ has been estimated [34,35]. In this thesis, we focus on the first problem – estimation of $h(t,\tau)$.

The two-dimensional channel model $h(t,\tau)$ contains too many parameters and must be simplified to facilitate TVCE. For examples, $h(t,\tau)$ is approximated by linear functions in [32] and by polynomials in [20]. The first model has smaller number of channel parameters and better ability to resist noises, but suffers from larger modelling error, while the latter one shows opposite proper-