A time-domain estimation method of rapidly time-varying channels for OFDM-based LTE-R systems


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ABSTRACT

This paper addresses the performance of fast doubly selective fading channel estimation combined with Inter-Carrier Interference (ICI) cancellation for Long Term Evolution (LTE) communication platform in the High Speed Railway (HSR) environment. We consider the Channel Impulse Response (CIR) coefficients with a critical Doppler frequency shift and multi-path fading that were taken from the WINNER II channel model and the D2a propagation scenario, where the conditions of HSR are analyzed. As multi-path fading increases and the channel varies in the order of the symbol period, we first propose a novel approach for designing a pilot symbol structure in the time domain. Then, we describe the deployment of the proposed pilot symbol structure to estimate the channel in the time domain. Channel information corresponding to the data positions is obtained by linear interpolation. In each OFDM symbol, the slope and the initial value for establishing an interpolation function are estimated to adapt to the time variation of the channel. An accurate estimate of channel state information is used for the purpose of ICI cancellation. The simulation results show that the channel estimated by our proposed method can follow the real channel well, even in a very high Doppler frequency. The estimation method in terms of Mean Squared Error (MSE) significantly outperforms the state-of-the-art methods. The combination of our channel estimator with several interference cancelers provides a considerably better system performance than that achieved when frequency channel estimation is used.

1. Introduction

The next generation of mobile broadband network standard (Next-G) uses Orthogonal Frequency Division Multiplexing (OFDM) modulation techniques, which have become a dominant technology employed in many wireless communication standards, forming the basis of Long Term Evolution (LTE), Digital Terrestrial Television Broadcasting (DTTB) and IEEE 802.11 families, etc., because OFDM can efficiently deal with frequency-selective channels caused by multi-path delays. Moreover, OFDM is very flexible for resource allocation and management, since it allows for dynamically assigning the subcarriers to multiple users and adaptively choosing the appropriate modulation and coding scheme.

With the development of high speed communication, transportation speed can increase up to 500 km/h [1], and LTE for Railway (LTE-R) has already become the communication standard in the High Speed Railway (HSR) environment [2,3]. A number of standardizations for HSR have been set up, which are known as the European Train Control System (ETCS) and the International Union of Railways (UIC). However, many problems exist as a result of the high speed, such as rapidly time-varying channels and large Doppler shifts (e.g., when users are moving at a speed of 500 km/h and a frequency of 2.6 GHz, the Doppler shift will increase to 1204 Hz in the LTE-R uplink system). In such a transmission scenario, the channels have a coherence time in the order of the symbol period, and it is thus preferable to estimate the channel by inserting a pilot into each OFDM symbol [4].

Accurate Channel Estimation (CE) and equalization for OFDM in doubly-selective (time and frequency) channels are challenging [5,6]. In principle, the solution for CE is based on inserting sufficient pilot symbols in transmitted data blocks and then using Least Squares (LS) and Minimum Mean Square Error (MMSE) in either the frequency or time domain.
Almost all the available CE methods assume that the channel does not vary within an OFDM symbol. This assumption, however, is not valid for LTE-R channels. Moreover, the CE methods in the frequency domain are not suitable for estimating the channels varying within an OFDM symbol. This is because, to perform a Fast Fourier Transform (FFT) operation, we have to assume that the channel is not changed during this operation. Thus, we developed a CE method in the time domain before the operation of the FFT at the receiver. The time resolution for interpolating the channel in the time domain is a sampling interval. Therefore, the proposed concept is applicable to rapidly time-varying channels. The key idea in the development of our method is the assumption that the channel is a linear function in each OFDM symbol. Moreover, we do not estimate the channel as a summation of all reflection paths. Instead, we estimate each channel path separately by using a special pilot symbol structure. In this structure, the pilot symbol is inserted in the time domain together with the data symbols. However, a zero sequence is inserted between the pilot and the data symbols. This is to protect the pilot from multipath reflection. Based on the pilot symbols received from all the multi-propagation paths, we can establish an assistive functionality to reconstruct the missing information of the channel at the position of the data symbols.

The rest of this paper is organized as follows. An overview of conventional CE and inter-carrier interference cancellation methods is given in Section 2. Section 3 introduces the Monte Carlo method used for modeling the fast-time-varying LTE-R channels. In Section 4, a novel CE method in the time domain for the LTE-R system is proposed. Our simulation results are discussed in Section 5. Finally, the paper is concluded in Section 6.

2. Overview of the conventional channel estimation and ICI cancellation methods

2.1. Channel estimation methods

CE methods in the frequency domain for estimating fast-time varying channels were proposed in [11–18]. The main drawback of CE in the frequency domain is that the FFT operation is required, whereby a number of data symbols are grouped into a block having the size of the FFT length. If the channel is changed during the FFT operation, then the estimated channel obtained from the post-FFT operation cannot reflect the variation in the real channel.

In the literature, many CE methods in the time domain have been presented, see, e.g., [19–21]. Almost all these methods are based on the correlation of the transmitted training sequence with that received in the time domain. Thus, the multipath components of the channel can be estimated for each period of sending the training sequence. However, the time variation of each multipath component within each channel estimation period is not detected. This is our motivation to propose a time-domain CE method, which is described in Section 4. To demonstrate the performance of our method, in Section 5 we compare it with that of some standard CE methods, such as the LS and MMSE techniques presented in [11,12].

2.2. Inter-carrier interference cancelation methods

The ICI cancellation methods for OFDM systems can be found in [22–25]. We classify these methods into two categories: ICI self-cancellation [23] and ICI cancellation by using the channel equalizer

$$h(t, t) = \sum_{\ell=1}^{N_p-1} h_\ell e^{j2\pi f_\ell (t-t_\ell)}$$

where the $N_p$ is the number of channel paths, $h_\ell$ is the amplitude of path $\ell$, and $t_\ell$ denotes time delay. The function $f_\ell(t)$ is the Doppler frequency of path $\ell$ observed at the absolute time $t$. $\theta_\ell$ denotes the Doppler phase of path $\ell$. For simplification, we can assume that $\theta_\ell = 0$. $t_\ell$ is the time delay of path $\ell$. The Monte Carlo channel modeling method presented in [14] is also a widely used method for modeling multipath channels. We used this method for the purpose of channel modeling. For implementing the Monte Carlo method, the Channel Impulse Response (CIR) in (1) is rewritten as

$$h(t) = \sum_{\ell=1}^{N_p} h_\ell e^{j2\pi f_\ell t}$$

where $f_\ell$ is the Doppler frequency of path $\ell$ in [21]. The category of ICI self-cancellation methods can be classified into three sub-categories: Adjacent self-Cancellation (AC) [26], Conjugate self-Cancellation (CC) [24], and Improved self-Cancellation (IC) [27]. Channel State Information (CSI) is essential for a high performance ICI-canceller. To demonstrate the relation between the ICI cancellation scheme and the CE performance, we combine our proposed channel estimator with various ICI cancellation schemes. In Section 5, we show that the combination of our proposed CE method with Jeon’s ICI-canceller significantly outperforms state-of-the-art methods.

3. Channel modeling for the multipath fast time-variant LTE-R channels

Channel modeling for the LTE-R channel is quite similar to that for the other mobile phone channels. This means that the multipath propagation and Doppler effects are the main properties that need to be modeled. One important characteristic of the channel that needs to be taken into account when modeling the channel is that it varies from symbol to symbol. This causes the channel to be highly time selective. A mathematical description of frequency-selective and time-variant channels is given in [28] as

$$h(t) = \sum_{\ell=1}^{N_p} h_\ell e^{j2\pi f_\ell t}$$

where $N_p$ is the number of channel paths, $h_\ell$ is the amplitude of path $\ell$, and $t_\ell$ denotes time delay. The function $f_\ell(t)$ is the Doppler frequency of path $\ell$ observed at the absolute time $t$. $\theta_\ell$ denotes the Doppler phase of path $\ell$. For simplification, we can assume that $\theta_\ell = 0$. $t_\ell$ is the time delay of path $\ell$. The Monte Carlo channel modeling method presented in [14] is also a widely used method for modeling multipath channels. We used this method for the purpose of channel modeling. For implementing the Monte Carlo method, the Channel Impulse Response (CIR) in (1) is rewritten as
where $f_d = f_{\text{max}} \sin(2\pi u_q)$, $\theta_d = 2\pi u_q$, and $M$ are the Doppler frequency, Doppler phase, and number of harmonic functions, respectively. $u_q$, a random variable in the range $[0,1]$, follows uniform distribution.

Because of the high speed of the train, the LTE-R channel changes within one OFDM symbol duration. In Fig. 1, we show the modeled channel with the parameters taken from [29], namely, a bandwidth of $B = 10$ MHz and $t_a = \frac{1}{\omega} = 100$ ns. The Power Delay Property (PDP) of the modeled channel is adapted from the WINNER II D2a model [30]. Because the PDP of the WINNER II D2a channel does not coincide with the sampling position of our simulated system, we need first to interpolate the WINNER II D2a channel with higher resolution, and then find the places where the sampling positions of the interpolated channel coincide with the system sampling positions. The values of the interpolated PDP at those positions form our modified PDP, which was used for modeling the simulated channel in this study.

Fig. 2 shows the amplitude of the multipath CIR for an example of the Doppler frequency of 1204 Hz. Fig. 3 illustrates the CIR of the first reflection path, which is modeled for different Doppler frequencies and is observed in two consecutive OFDM symbols. In both Figs. 2 and 3, we can see that the shape of the channel is close to a linear function of time. The time variation of the channel depends on the Doppler frequencies. To estimate the channel, we need to develop a deterministic function that reflects the variation in the channel. The observation results of the simulated channel provide us with a basis for assuming that the channel is a linear function within an OFDM symbol. This assumption is closer to the fact for low Doppler frequencies. This assumption is the background on which we developed our novel CE method, presented in Section 4.

The Doppler effect is modeled on the basis of the presence of the LoS component as modeled in the WINNER D2a scenario. In these cases, the Doppler spectrum associated with the LoS component is dominated in comparison with other components.

4. Proposed time domain channel estimation method

In order to estimate the CIR, we propose an OFDM symbol structure, which is presented in Fig. 4. In this structure, pilot symbols are inserted into an OFDM symbol in the time domain, as shown in Fig. 4. The pilot signal has $2G + 1$ samples ($G$ is the guard interval sequence length). The first and last $G$ samples are set to be zero, and thus only one sample at the $(G + 1)\text{th}$ position has an amplitude of $P$ ($P \neq 0$). The pilot symbol is sent out from the transmitter with the period of an OFDM symbol and is received at the receiver. After multipath propagation, the received pilot symbols display the CIR, as shown in Fig. 4 (see Fig. 5).

Assuming that the CIR has $N_P$ paths, each channel path varies in a linear fashion during a period of an OFDM symbol, and in an additional duration of the last received pilot symbol from multipath propagation in the next OFDM symbol, i.e., $2T_G$, as illustrated in Fig. 4. Thus, a period of linear assumption of the CIR of each channel path is $T_S + 2T_G$, where

![Fig. 5. Illustration of the linear variation of each channel path in the time domain.](image-url)
\( T_G = G \times \tau_0 \) is the duration of the guard interval. We denote by \( \tau_0 \) the sampling interval. The structure of an OFDM symbol is shown in Fig. 4. Considering the OFDM symbol \( i \) and the propagation path \( l \), let \( N_{FFT} \) be the FFT length and \( N_P \) is the number of propagation paths. We can write the CIR of the channel path \( l \) as a function of time as

\[
\tilde{h}_l(t) = \tilde{h}_l + s_l t' 
\]

with \( 0 \leq t' \leq T_x + 2T_G \), and \( t = iT_x + t' \). \( s_l \) is the slope of the linear function, which models the channel in the \( l \)th path and within the interval of the OFDM symbol \( i \). \( \tilde{h}_l = \tilde{h}(t_l, iT_x) \) is the initial value of the assumed linear channel function of the \( l \)th path at the absolute time \( t = iT_x \). \( T_x = (N_{FFT} + 2G + 1) \tau_0 \) is the OFDM symbol duration, as shown in Fig. 4. The number of sampling intervals in an OFDM symbol is \( N_S = N_{FFT} + 2G + 1 \).

The received signal corresponding to the \( i \)th transmitted OFDM symbol can be written as

\[
y_i(t) = \sum_{l=0}^{N_P-1} h_l(t) x_i(t - t_l) + w_i(t) 
\]

where \( t_l \) is the propagation delay of the \( l \)th path. Now, we describe the discrete received signal by replacing the continuous variable by the discrete one, namely, by replacing \( t \) by \( t_k = k\tau_0 \), and \( t' \) by \( t'_l = l\tau_0 \), \( k \) is the sampling time index, and takes the value \( k = 0, 1, \ldots, N_{FFT} + 2G \). Then,

\[
y_i(t_k) = \sum_{l=0}^{N_P-1} h_l(t_k) x_i(t_k - t_l) + w_i(t_k) 
\]

After discretization, the received signal is written as

\[
y[k] = \sum_{l=0}^{N_P-1} h_l[k] x[k - l] + w[k] 
\]

The received signal at the sampling index \( k = G \) at the OFDM symbol \( i \), at the time instance \( t_0 = G \times \tau_0 \) is

\[
y_i[G] = \sum_{l=0}^{N_P-1} h_l[G] x_i[G - l] 
\]

Because of the properties of the used pilot structure, the condition in (8)

\[
x_i[k] = \begin{cases} 
0 & \text{if } 0 \leq k \leq G - 1 \text{ and } G + 1 \leq k \leq 2G \\
P & \text{if } k = G 
\end{cases}
\]

is fulfilled. This leads to

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**Fig. 6.** Illustration of the time variation of the CIR of a channel path, which can be approximated by a linear function in each OFDM symbol.

**Fig. 7.** Flowchart of the proposed channel estimator.

\[ y_i(G) = h_{0i}(G) \times x_i(G) = h_{0i}(G) \times P. \]  

(9)

Similarly, we observe the received signal at the sampling index \( k = G + l \) as

\[ y_i(G + \ell) = h_{0i}(G + \ell) \times P \]  

(10)

Now, we observe the received pilot symbol at the sampling index \( k = G + l \), however at OFDM symbol \( i + 1 \). The received signal corresponding to channel path \( l \) and at the sampling index can be \( k = G + l \), written as

\[ y_{i+1}(G + \ell) = h_{i+1}(G + \ell) \times P \]  

(11)

We assume that the CIR of the channel path \( l \) is still a linear function within an interval \( 0 \leq t \leq T_s + 2T_{\text{ta}} \), as given in (3). Then, the received signal \( y_{i+1}(G + \ell) \) can be written as

\[ y_{i+1}(G + \ell) = \tilde{h}_i(G + \ell + N_3) \times P \]  

(12)

Based on the assumption given in (3), it is easy to prove that

\[ \tilde{h}_i(G + \ell + N_3) - h_{0i}(G + \ell) = s_{i+1} \times T_s \]  

(13)

By replacing \( h_{0i}(G + \ell) \) by \( \tilde{h}_i(G + \ell) \) in (10) and using the relations given in (10), (12), and (13), we can derive that

\[ y_{i+1}(G + \ell) - y_i(G + \ell) = s_{i+1} \times P \times T_s \]  

(14)

From (14), we can calculate the slope value of the assumed linear channel function within the OFDM symbol \( i \) as

\[ s_{i+1} = \frac{y_{i+1}(G + \ell) - y_i(G + \ell)}{P \times T_s} \]  

(15)

On the basis of the obtained \( s_{i+1} \), we can determine the initial value \( \tilde{h}_i \) of the assumed linear function of the CIR of the \( i^{th} \) path at the OFDM symbol \( i \) as

\[ \tilde{h}_i = h_{0i}(G + \ell) - (G + \ell) \times T_s \times s_{i+1} \]

\[ = y_i(G + \ell) \times P - (G + \ell) \times T_s \times s_{i+1} \]  

(16)

Knowing the slope value of the assumed linear channel function and the initial value of the CIR, we reconstruct the channel with the \( i^{th} \) OFDM symbol. This process is continued to estimate the subsequent OFDM symbol, as depicted in Fig. 6. The flowchart of the proposed algorithm for CE is illustrated in Fig. 7.

5. Simulation results

In this section, the performance of the proposed channel estimator is analyzed, and then we demonstrate the system performance obtained by combining the CE with various interference cancellation schemes. The block structure of the simulated system is shown in Fig. 8, where the proposed CE in the time domain is applied to estimate the channel. Then, the estimated CSI is used for ICI cancellation. To simulate the system, we adopted the parameters from the LTE-R system that can be seen in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
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<tr>
<td>Carrier frequency (GHz)</td>
<td>0.7, 1.8, 2.6</td>
</tr>
<tr>
<td>Channel bandwidth (MHz)</td>
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</tr>
<tr>
<td>Channel type</td>
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</tr>
<tr>
<td>Number of the FFT</td>
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</tr>
<tr>
<td>Sampling interval</td>
<td>( \tau_s = 100 \text{ ns} )</td>
</tr>
<tr>
<td>Mobility (km/h)</td>
<td>300, 500</td>
</tr>
<tr>
<td>Antenna configuration</td>
<td>SISO</td>
</tr>
<tr>
<td>Modulation mode</td>
<td>16 QAM</td>
</tr>
</tbody>
</table>

5.1. Channel estimation performance

Figs. 9 and 10 show the real and imaginary terms of the three different channel paths of the simulated CIR channel with the PDF given in Fig. 1. One is the original channel and the second is the estimated channel obtained by the proposed method. The observation time is 10 consecutive OFDM symbols. We can see that, although the channel varies within one OFDM symbol, the proposed method tracks the channel well.

Figs. 11–13 show the results in terms of the Mean Squared Error (MSE) of the estimated channel in comparison with the state-of-the-art methods, where the results are simulated for different Doppler frequencies.

The pilot structure plotted in Fig. 14 is used for the frequency CE methods proposed in [11,12]. Additionally, we chose the pilot distance in
the frequency domain $D_f = 64$, the selection of which was based on the maximum time delay of the LTE-R channel [29]. In contrast, the novel pilot structure in the time domain, in Fig. 4, is applied to our proposed time domain CE.

It can be seen in Figs. 11–13 that the proposed method significantly outperforms the standard methods. In our comparison, all methods used the same number of pilot symbols per each OFDM symbol. Fig. 15 shows the results of the MSE of the estimated channel obtained by the proposed method for different Doppler frequencies. Increasing the Doppler frequency leads to an increase in the MSE. This is because, if our assumption that the channel varies linearly within one OFDM symbol is no longer valid, then our proposed method is not able to estimate the channel.
5.2. Interference cancellation performance

Figs. 16–21 demonstrate the system performance in terms of the Symbol Error Rate (SER) obtained by various ICI cancellation schemes, where the AC [26] and the IC method [27] have to use the CE in the frequency domain. This is because it is not possible to arrange the pilot symbols in the time domain to meet the condition of interference self-cancellation for both the AC and the IC method. It is noted that the data rate is reduced by a half or quarter if the AC or the IC method, respectively, is applied. Jeon’s method [22] uses the CE in the time domain, and thus can be combined with our channel estimator for the purpose of interference cancellation. In all the simulation results, in terms of the SER the combination of our CE method with Jeon’s interference cancellation scheme shows the highest system performance. In addition, this combination does not lead to a reduction in the data rate. Therefore, it could be a good candidate for the purpose of ICI cancellation in LTE-R networks (see Fig. 21).

Fig. 15. The MSE of the estimated channel obtained by the proposed method for channels with different Doppler frequency.

Fig. 16. Comparison of the SER of the proposed method and some ICI cancellation methods with Doppler frequency of $f_{\text{Dmax}} = 194$ Hz.

Fig. 17. Comparison of the SER of the proposed method and some ICI cancellation methods with Doppler frequency of $f_{\text{Dmax}} = 324$ Hz.

Fig. 18. Comparison of the SER obtained by using different ICI cancellation methods and in the condition of a Doppler frequency of $f_{\text{Dmax}} = 500$ Hz.

Fig. 19. Comparison of the SER obtained by using different ICI cancellation methods and in the condition of a Doppler frequency of $f_{\text{Dmax}} = 722$ Hz.

Fig. 20. Comparison of the SER obtained by using different ICI cancellation methods and in the condition of a Doppler frequency of $f_{\text{Dmax}} = 833$ Hz.
6. Conclusion

In this paper, we proposed a channel estimation method implemented in the time domain, whereby the pilot symbols are inserted such that each channel path is detected under the assumption that the channel is a linear function in one OFDM symbol. The proposed method can be applied for a very fast time-varying channel, such as the LTE-R channel, where the channel varies within an OFDM symbol. Our simulation results in terms of the MSE show that our proposed method significantly outperforms the state-of-the-art methods. The knowledge of the channel information at the receiver is a good basis for our development of an effective ICI cancellation scheme for LTE-R systems. We tested the proposed mechanism in different cases of maximum Doppler frequency, varying from 194 to 1204 Hz. The simulation results show that the proposed CE significantly outperforms state-of-the-art methods. Clearly, for a very high Doppler frequency, the linear assumption for the variation in the channel is no longer valid. This causes a degradation of the system performance. Our future work is to extend our concept presented in this paper to mitigate the interpolation error.

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