Channel Estimation Schemes for IEEE 802.11p Standard

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Abstract—In vehicle-to-vehicle (V2V) communications, reliable channel estimation is critical for the system performance due to the extremely time-varying characteristic of V2V channels. In this article, we present a survey on the current channel estimation techniques for the IEEE 802.11p standard. According to deficiencies of the current schemes and considering characteristics of V2V channels, we propose a novel channel estimation scheme, which utilizes the data symbols to construct pilots as well as the correlation characteristics between channels within two adjacent symbols. Analysis and simulation results demonstrate that the proposed scheme outperforms currently widely-used schemes especially in high signal-to-noise ratio regime. At the end, some open issues for the future work conclude this article.

I. Introduction

In the recent years, traffic accidents have become one of the leading causes for death all over the world, hence road safety has been greatly concerned. At the same time, we are facing the pressing needs for convenience and commercial oriented applications onboard [1] [2]. Vehicle-to-vehicle (V2V) communication, as a promising technique of intelligent transportation system, has been proposed to

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meet these needs. Over the past decade, V2V communications have attracted a lot of attention and various applications have been developed, such as the cooperative forward collision warning, traffic light optimal speed advisory, remote wireless diagnosis [3], etc. In 2010, after a few years's test run, IEEE 802.11p standard, which is also referred to as dedicated short range communications standard [4], has been officially implemented.

A precisely estimated channel response is critical for the follow-up equalization, demodulation, and decoding, showing that the accuracy of the channel estimation decides system performance.

Channel estimation technique plays an important role for the design of any communication systems. As far as we know, a precisely estimated channel response (CR) is critical for the follow-up equalization, demodulation, and decoding. Therefore, generally speaking, the accuracy of the channel estimation decides system performance. However, for wireless systems, radio propagations can be easily influenced by environments, relative velocity, etc, it is hard to foresee the variation of channels. Therefore, accurately and efficiently estimating wireless channels is far more challenging compared with tracking wired channels.

For V2V communication systems, the design of channel estimation technique is much more difficult and significant than any other wireless systems. However, the IEEE 802.11p is originally derived from the well known standard IEEE 802.11a, which was initially designed for relatively stationary indoor environments, without considering the impact of high mobility. This results in the current IEEE 802.11p standard having several deficiencies to properly suit high dynamic property of V2V channels. This article focuses on one of the most important challenge among these deficiencies: how to properly design the channel estimation module for IEEE 802.11p standard. In general, there are two basic manners. The first one needs the modification of the structure of the IEEE 802.11p [5]–[8], while the other one can remain the structure of the IEEE 802.11p standard [8]–[12]. By thoroughly analyzing currently available channel estimation techniques, belonging to the aforementioned two manners, for V2V communications, this article summarizes the advantage and disadvantage of them. Based on these interesting analysis, a novel channel estimation scheme is proposed in this article, which belongs to the second manner, i.e., without changing the current structure of the IEEE 802.11p standard. The proposed scheme first utilizes data symbols to construct pilots and then exploits the correlation characteristics between channels within two adjacent symbols in order to improve the accuracy of the channel estimates. Simulation results demonstrate the excellent performance of the proposed channel estimation scheme for V2V communications.

The rest of this article is organized as follows. In Section II, we introduce the structure of IEEE 802.11p and the channel scenarios adopted for the simulation. Then, Section III addresses the state-of-the-art in the channel estimation techniques for V2V communications. A detailed analysis for the current schemes will be given in this section. Section IV proposes a novel channel estimation scheme. In Section V, simulation results are presented for performance comparison. Finally, Section VI concludes this article with some open issues.

II. System Model

A. Structure of IEEE 802.11p

The IEEE 802.11p physical layer is based on orthogonal frequency division multiplexing (OFDM). The OFDM technique transmits data on closely spaced orthogonal subcarriers, thus it can improve the efficiency of spectrum and

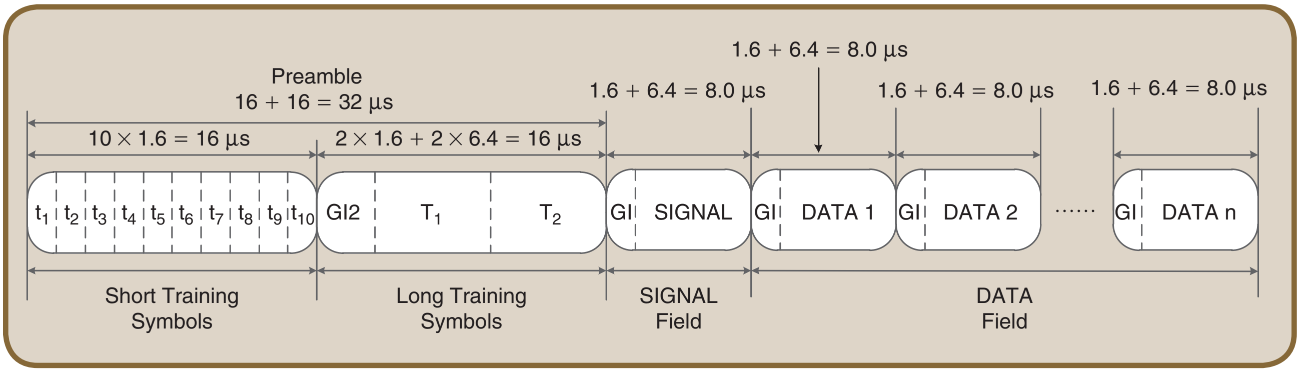

FIG 1 IEEE 802.11p packet preamble structure.

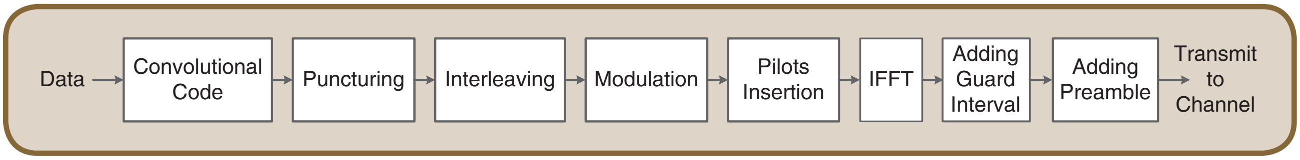

FIG 2 Block diagram of the IEEE 802.11p transmitter.

cope with severe channel conditions. Depending on different modulation and puncturing schemes, it can support data transmission rates ranging from 3 to 27 Mbit/s. The packet preamble structure of the IEEE 802.11p is shown in Fig. 1. It has almost the same structure as that of the IEEE 802.11a except the doubled symbol duration. Each packet consists of preamble including short training symbols and long training symbols, SIGNAL field, and DATA field in which the SIGNAL field conveys information about the type of modulation, the coding rate, and etc, while the DATA field is mainly consisted of the transmitted data. The ten 1.6 µs short training symbols (t_1 to t_{10}) located at the beginning of every packet are used for coarse synchronization. The follow-up two 6.4 µs long training symbols T_1 and T_2 are used for fine synchronization and channel estimation. The guard interval (GI) is inserted so as to mitigate inter-symbol interference. The SIGNAL field consists of only one OFDM symbol, while the number of symbols in DATA field is not explicitly defined.

Fig. 2 depicts the general block diagram of the IEEE 802.11p transmitter. A convolutional encoder is employed at the beginning for forward error correction. Higher data rate can be gained by using puncturing, e.g., 2/3 and 3/4. The coded data is then interleaved so as to mitigate burst errors caused by pulse noises. Afterward, a modulation such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (16QAM) or 64 quadrature amplitude modulation (64QAM) is implemented. The following 64-point inverse fast fourier transform (IFFT) realizes OFDM modulation. The 64 OFDM subcarriers include 48 data subcarriers and 4 phase tracking pilot subcarriers, which are located on subcarriers −21, −7, 7, and 21, and used for compensating the common phase rotation caused by the residual frequency offset. In addition, 11 virtual subcarriers as well as a direct current subcarrier are also added to realize 64-point IFFT. Finally, GI and preamble are inserted. The specific parameters of the IEEE 802.11p are shown in Table 1.

B. Channel Model

The characteristics of wireless channels, especially for V2V channels have been investigated in a number of literature (see [13]–[24] and references therein). In [21] and [23], two different kinds of classical tapped delay line (TDL) channel models were proposed. The former one is a wide stationary uncorrelated scattering (WSSUS) model, while the latter one is a non-WSSUS model.

In this article, we adopt the channel model proposed in [21] and [22], which is accepted as the standard V2V channel model in the IEEE 802.11p. The measurement campaign was implemented in the metropolitan Atlanta, Georgia area including six scenarios, i.e., vehicle-to-vehicle (VTV) Expressway Oncoming, VTV Urban Canyon Oncoming, roadside-to-vehicle (RTV) Suburban Street, RTV Expressway, VTV Expressway Same Direction with Wall, and RTV Urban Canyon. The characters of the six V2V channels are demonstrated in Table 2 according to the data given in [21] and Doppler power spectral density of each tap shown in [22].

The applied V2V channel model in this article is a standard TDL model, therefore, the generation of the channel follows the classic rule for creating a TDL channel model as shown in [21] and [22]. Since the Doppler power spectral density of each tap has been obtained based on real measurement data, the channel generated has obvious time-varying characteristic. Based on the standard channel models in [21], [22] and to express the time-variant property of V2V channels, the CR is generated in every sampling time, i.e., 100 ns. Therefore, the channels are dynamic over the period of one OFDM symbol. It is noticeable that channel

Table 1. Parameters of the IEEE 802.11p.

Parameter	Value
Bandwidth (MHz)	10
Bit rate (Mbit/s)	3, 4.5, 6, 9, 12, 18, 24, 27
Modulation schemes	BPSK, QPSK, 16QAM, 64QAM
Code rate	1/2, 2/3, 3/4
Data subcarriers	48
Pilot subcarriers	4
Total subcarriers	52
Fast Fourier Transform (FFT) size	64
FFT period (µs)	6.4
GI duration (µs)	1.6
Symbol duration (µs)	8.0
Subcarrier frequency spacing (MHz)	0.15625
Error correction coding	$k = 7$ (64 states) convolutional code

Table 2. Characters of the six V2V channel models.

Scenario	Velocity (km/h)	Doppler Shift (Hz)	Maximum Excess Delay (μs)
VTV expressway oncoming	104	1000–1200	0.3
RTV urban canyon	32–48	300	0.5
RTV expressway	104	600–700	0.4
VTV urban canyon oncoming	32–48	400–500	0.4
RTV suburban street	32–48	300–500	0.7
VTV expressway same direction with wall	104	900–1150	0.7

time-variant characteristic will result in intercarrier interference (ICI), which will degrade the OFDM performance [24]. However, it is not the focus of this paper and the impact of ICI is not considered in this paper.

Due to the page limit, we cannot give all the simulation results under the six vehicular scenarios introduced in [21] and [22]. The simulations in this article are derived from three representative scenarios, i.e., VTV Expressway Oncoming, RTV Urban Canyon, and VTV Urban Canyon Oncoming. These three scenarios have covered typical vehicular environments including different communication types (VTV/RTV), different speeds (low velocity/high velocity), and a wide range of Doppler shift (300–1200 Hz).

III. Overview of Current Channel Estimation Schemes

As introduced in Section II, the placement of pilot symbols in the OFDM time-frequency grid is of crucial importance for channel estimation. In view of this aspect, the IEEE 802.11p pilot setup appears to be infeasible for tracking channel especially in rapid motion. This is because that on one hand, two long training symbols cannot support reliable variation in the frequency domain. Attentive to these limitations, two categories of channel estimation manners have been particularly proposed to tackle this problem. In this section, the presentative channel estimation schemes belonged to the above mentioned two manners are briefly described and their performances are compared.

A. Manner 1: Modify the Structure of the IEEE 802.11p

1) Midamble Based Channel Estimation Scheme

This approach was proposed in [5] and [6] to alleviate the impact from the dynamic nature in vehicular environments. The midambles are inserted periodically between the data symbols. The DATA field can be arbitrarily long, provided that the number of midamble sequences is sufficient. It first performs the initial channel estimation via the preamble, i.e., the two long training symbols. The estimated CR is then employed to equalize the subsequent data symbols. This procedure keeps on until the first midamble provides channel update and tracking. The estimation for the follow-up midamble-data symbol blocks take the same procedure as the first one, except that there is no need for the initial estimation. In this work, a midamble insertion ratio γ was introduced which represents the ratio of data symbol to midamble. Simulation results show that with minor γ, a remarkable performance enhancement is achievable, especially for 16QAM modulation. However, the midamble based estimation scheme obtains performance improvement at the expense of spectrum efficiency and results in a lower transmission rate. Meanwhile, to fulfill the required bit error rate (BER) and transmission rate, the choice for optimum γ under different V2V channel and packet size is still an unsolved issue.

2) Time Domain Least Square Estimation (TDLSE) Scheme

In [7] and [8], a scheme called TDLSE was proposed for tracking vehicular communication channels. The underlying idea was originally provided in [26] and later under further exploitation in a number of literature (see [27]–[29] and references therein). By following this idea, the authors in [7] and [8] proposed to insert a Zadoff-Chu sequence or a pseudo-noise (PN) sequence into the prefix for further facilitating the channel estimation. Specifically, the channel impulse response (CIR) is first derived by using least square (LS) estimation from the received signal and a transmitted matrix which is comprised of the replaced prefix, namely Zadoff-Chu sequence or PN sequence. Furthermore, in this work, the estimated CR is further averaged with the adjacent several symbols. Finally, an LS equalization is performed. Simulation results demonstrate that both Zadoff-Chu sequence based TDLSE and PN sequence based TDLSE can achieve significant performance improvement compared with other channel estimation schemes.

B. Manner 2: Remain the Structure of the IEEE 802.11p

1) LS Estimation Scheme

A common manner of channel estimation for the IEEE 802.11a is the LS estimation. It jointly makes use of the received preamble $R_{T_1}(k)$ and $R_{T_2}(k)$ ahead of data symbols, i.e., the two long training symbols T_1 and T_2 shown in Fig. 1, to estimate the CR

$$H(k) = \frac{R_{T_1}(k) + R_{T_2}(k)}{2X(k)}, \tag{1}$$

where $X(k)$ is the predefined frequency domain long training symbol. The CR derived from (1) is then used for the subsequent equalization assuming that the channel is stationary for the whole packet. However, actually, the V2V channel changes very fast and thus the LS estimation will significantly deteriorate the system performance in a practical use.

2) Wiener Filter Based Estimation Scheme

Since LS estimation is unable to cope with the rapidly changing channel conditions, an approach using Wiener filter was proposed in [9]. The Wiener filter is implemented between the channel estimation and the equalizer by searching the optimal coefficients to minimize the mean square error (MSE) of the CR before and after Wiener filtering. To realize effective channel estimation, the Wiener filter design is of crucial importance. It is based on three parameters, including the received signal-to-noise ratio (SNR), the maximum excess delay $\tau_{\max}$, and the shape of the power delay profile (PDP) $P(\tau)$.

The derivation of these three parameters are challenging, especially for the vehicular environments. The simplest one is the estimation for the received SNR, which can be calculated according to the method addressed in [30]. However, it is tough to obtain the maximum excess delay $\tau_{\max}$ and the shape of the PDP. The only way is by approximation in which $\tau_{\max}$ can be defined as 1.6 μs, i.e., the duration of GI, and the PDP shape can be approximated to a rectangular or an exponentially decaying PDP.

Simulation results illustrate that by applying Wiener filter, the MSE remarkably decreases. Therefore, the packet error rate (PER) has been significantly improved. However, due to the uncertainties caused by the assumptions for $\tau_{\max}$ and $P(\tau)$, the performance of the Wiener filter based channel estimation scheme is suboptimal.

3) Generalized Discrete Prolate Spheroidal (DPS) Sequences Based Channel Estimation Scheme

In [10], a robust iterative channel estimator was proposed based on generalized DPS sequences. According to the theory, the DPS sequences can tighten the subspace design, and meanwhile, the iterative estimation mechanism supplies additional pilot information.

The concept of the DPS sequences was investigated in [31]. Due to page limit, its related literature are not introduced here or listed in the bibliography. The generalized DPS sequences enable the subspace to be tight enough that the MSE is minimized. By utilizing the generalized DPS sequences, the channel estimation is simplified and only the DPS coefficients are needed to estimate. Since the iterative algorithm of the generalized DPS sequences based scheme has high computational complexity, to deal with this problem, an improved pilot symbol pattern was proposed in this work. The kernel is a postamble appended after the DATA field. Even though the postamble may reduce computational complexity, it will decrease efficiency and cause incompatibility.

4) Spectral Temporal Averaging (STA) Estimation Scheme

To alleviate the adverse impact raised by time-variant channels, a scheme called STA was proposed in [11]. In this work, STA was defined as an enhanced equalization scheme, but actually, it is an approach to estimate the dynamic channels.

In the STA scheme, the $(i-1)$th estimated CR $H_{\mathrm{STA},i-1}(k)$ is first used to equalize the received data symbol $S_{R,i}(k)$ gives

$$\hat{S}_{T,i}(k) = \frac{S_{R,i}(k)}{H_{\mathrm{STA},i-1}(k)}, \tag{2}$$

where i represents the number of the data symbol and $H_{\mathrm{STA},0}(k)$ is derived from (1) by using the two long training symbols and defined as the 0 th data symbol's CR. Note that, the bits on the 4 phase tracking pilot subcarriers are not equalized in (2). $\hat{S}_{T,i}(k)$ is then demapped to obtain $\hat{X}_i(k)$. For completeness, those $\hat{X}_i(k)$ with $k=-21,-7,7,21$, i.e., the demapped bits on the phase tracking pilot subcarriers, are endued with the frequency domain values predefined in the standard. The initial channel estimate, $H_i(k)$ is estimated as

$$H_i(k) = \frac{S_{R,i}(k)}{\hat{X}_i(k)}. \tag{3}$$

It was further considered in [11] that since $H_i(k)$ was derived directly from the data symbols which may be incorrectly demapped, an averaging of the initial estimates in both frequency and time domain was needed to improve the accuracy. The frequency domain averaging is implemented as

$$H_{\mathrm{update}}(k) = \sum_{\lambda=-\beta}^{\lambda=\beta} \omega_\lambda H_i(k+\lambda), \tag{4}$$

where $2\beta+1$ represents the number of subcarrier that is averaged and ω_λ is a set of weighting coefficients with unit sum which are often assumed as an equal value, i.e., $\omega_\lambda = 1/(2\beta+1)$. The time-domain averaging is completed as follows which also turns out to be the final channel estimate,

$$H_{\mathrm{STA},i}(k) = \left(1-\frac{1}{\alpha}\right)H_{\mathrm{STA},i-1}(k) + \frac{1}{\alpha}H_{\mathrm{update}}(k), \tag{5}$$

where α is an updating parameter related to the Doppler spread. The parameters α and β depend on the different types of V2V channels. To ensure accuracy, α and β should be determined from the knowledge of the radio environment, e.g., from global positioning system (GPS) and map knowledge referred in [11]. However, it is hard to obtain these kind of environment information in practice. Therefore, it was suggested in [11] that for simplicity and convenience, fixed values were chosen with performance degradation at an acceptable level.

5) Decision-Directed Channel Estimation Scheme

In [12], a channel tracking technique called decision-directed scheme was proposed to adjust the vehicular time-variant channels which mainly contains channel tracking and smoothing. The initial channel estimation is performed by employing the preamble as the aforementioned midamble based estimation scheme does. Then, the subsequent symbols are estimated one by one in a specified order, including equalizing, decision-directed estimation, and smoothing.

The channel tracking principle of the decision-directed estimation is similar to the first two steps in the STA scheme, i.e., equations (2) and (3). At low SNR regime, the decision directed channel tracking suffers from error propagation due to wrong decisions. Therefore, a smoothing technique which removes a part of estimation noise was proposed to cope with the aforementioned drawback. Even though the simulation exhibits that the decision-directed scheme may achieve performance enhancement, the smoothing operation brings about huge computational complexity due to a multiplication of large matrixes. To reduce computational complexity, two algorithms have been introduced. The first one, named lossless complexity reduction, utilizes singular value decomposition to reduce matrix multiplication, and at the same time, it does not cause performance loss. While the other one, named lossy complexity reduction, reduces the complexity at the price of performance degradation by ignoring some subcarriers in the smoothing process.

6) Pseudo-Pilot Channel Estimation Scheme

In [8], a channel estimation scheme called pseudo-pilot technique was proposed besides TDLSE technique. The principle of the pseudo-pilot estimation scheme was originally proposed in [32] and [33], in which the pseudo-pilots were regarded as true pilots. It is based on a regression polynomial to describe the CR process [34]. The least-squares-fitting (LSF) for calculating the regression polynomial coefficients was investigated in [34] and [35].

The pseudo-pilot technique is comprised of three steps—precalculation, real-time estimation, and channel tracking. The precalculation necessitates predefining the regression polynomial and prestoring the related matrix for the follow-up steps. The real-time estimation first calculates the CIR on the pilot subcarriers, and then estimate the whole CIR using LSF. Next, the estimated whole CIR is employed to derive relatively accurate CR by utilizing the technique similar to the decision-directed channel tracking. The last step in [8], i.e., channel tracking, is an improvement for the original pseudopilot algorithm [32] and [33], which has combined with the packet structure of the IEEE 802.11p. The preamble first provides initial coefficient for the channel tracking and the pilots are then utilized to track the channel variation of the adjacent symbols. It is predictable that with the assist of the channel tracking technique, the performance of the pseudopilot algorithm is enhanced.

C. Comparison of the Current Channel Estimation Schemes

Table 3 briefly summarizes the comparison of the current schemes including three improved approaches. From Table 3, it is evident that only three schemes necessitate modifications for the IEEE 802.11p standard and may result in compatibility reduction with other receivers. At the same time, except TDLSE, the efficiency of these

Table 3. Comparison of the current v2v channel estimation schemes.

Channel Estimation Schemes	Modify the Standard or Not	Need Channel Information or Not	Computational Complexity	Compatibility	BER Performance
Midamble based scheme [5], [6]	Yes	No	cl.2	Reduced	pl.1–pl.3
TDLSE scheme [7], [8]	Yes	No	cl.2	Reduced	pl.2
LS scheme	No	No	cl.1	Invariant	pl.5
Wiener filter based scheme [9]	No	Yes	cl.3	Invariant	pl.3
Generalized DPS based scheme [10]	No	Yes	cl.5	Invariant	pl.3
Improved generalized DPS based scheme [10]	Yes	Yes	cl.4	Invariant	pl.3
STA scheme [11]	No	Yes	cl.3	Invariant	pl.2
Decision-directed scheme [12]	No	Yes	cl.5	Invariant	pl.3
Improved decision-directed scheme (lossless complexity reduction) [12]	No	Yes	cl.4	Invariant	pl.3
Improved decision-directed scheme (lossy complexity reduction) [12]	No	Yes	cl.5	Invariant	pl.3/pl.4
Pseudo-pilot scheme [8]	No	Yes	cl.5	Invariant	pl.3/pl.4

[1] cl. represents complexity level, cl.1 means very low computational complexity and cl.5 means very high computational complexity.

[2] pl. represents performance level, pl.1 means excellent performance and pl.5 means a severe performance degradation.

schemes will be reduced either. For the majority of the schemes which adhere to the standard packet structure, they need some channel information in advance to ensure preferable performance. For instance, the Wiener filter based channel estimation scheme needs prior knowledge about the maximum excess delay and the PDP shape of the V2V channels which are difficult to acquire. If constant values are given instead of the actual values, the estimation performance will be suboptimal. For the schemes which modify the current standard, it is predictable that they express relatively lower computational complexity. Except the LS scheme, the rest estimation schemes of the second manner for the standard IEEE 802.11p have higher complexity mostly originated from matrix multiplication, which may challenge the hardware design. As for the comparison of the performance, it is noticeable that three of them need close adaptation to the channel. The reason is mainly due to the parameters used in these three schemes are not constant and better performance relies on reasonable values. In addition, it is unavoidable that the schemes which adhere to the standard suffer from performance degradation and an increase of the computational complexity.

IV. CDP Channel Estimation Scheme

Although the aforementioned schemes are effective in estimating the channel in some cases, they still have several limitations, e.g., limited packet length, higher computational complexity, and impractical application due to the necessitation of the channel information. In order to improve the performance of the channel estimation in time-variant V2V channels, we introduce a novel estimation scheme by using preamble-based estimated CR and constructed data pilots (CDP).

Although the V2V channels have extremely dynamic nature in the time domain, the correlation characteristic of the CR between the adjacent two data symbols is high. We can derive the cross-correlation of the adjacent symbols by exploiting the four phase tracking pilots, which is higher than 0:7. Therefore, the correlation characteristic can be utilized which has not been considered in the current channel estimation schemes.

Fig. 3 shows the block diagram of the receiver, in which the red box demonstrates the CDP estimator, which is implemented between the FFT and demodulation operations. While Fig. 4 illustrates the schematic structure of the CDP estimator, where $S_{R,i}(k)$ is the frequency-domain received symbol on the kth subcarrier obtained from FFT, i.e., OFDM demodulation. Note that, k represents the 48 data subcarriers without taking consideration of the 4 pilot subcarriers. The CDP estimator comprises five steps, i.e., equalization, constructing data pilot, LS estimation, estimation and demapping, and comparison. The first three steps are similar with those in STA and decision directed scheme, while the latter two utilize the correlation characteristic to improve the performance in the high SNR regime, which is the notable difference between CDP and STA, as well as decision-directed scheme. The detailed explanations of the aforementioned five steps are listed as follows.

Step 1—Equalization

As shown in Fig. 4, CDP estimator iteratively updates the channel estimate employing the previous symbol's CR since the CR of the adjacent two data symbols have high correlation. We can assume that the CR of the current ith symbol is unchanged. Therefore, the first step—equalization is performed as

$$\hat{S}_{T,i}(k) = \frac{S_{R,i}(k)}{H_{\text{CDP},i-1}(k)}, \tag{6}$$

where $H_{\text{CDP},i-1}(k)$ is the output of the previous estimation process, i.e., $(i-1)$th symbol's estimated CR.

Step 2—Constructing Data Pilot

$\hat{S}_{T,i}(k)$ is then demapped to construct data pilots $\hat{X}_i(k)$ namely the core of the proposed scheme. It is common sense that data symbols can hardly provide useful channel information. Thus, in the previous channel estimation approaches, CRs are usually estimated via preambles and pilots instead of data symbols. However, as a matter of fact, data symbols are available for channel estimation, which can be demapped to the corresponding constellation points to construct "pilots", i.e., the data pilots in the CDP scheme.

The principle of the CDP estimator is depicted in Fig. 5. Owing to the impacts of noise and other interferences, $\hat{S}_{T,i}(k)$ is possibly located into the wrong regions, i.e., the shadow area. Therefore, $\hat{X}_i(k)$ is easily to be demapped to the incorrect constellation points. With the assist of demapping, the impact from noise and interferences may be partially alleviated. The remaining error can be further mitigated in the following steps by exploiting the correlation characteristics between channels within two adjacent symbols.

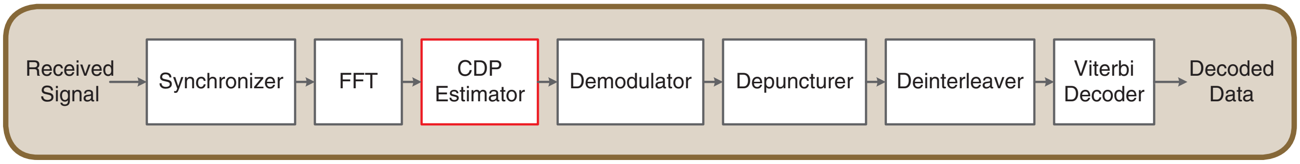

FIG 3 Structure of the CDP receiver.

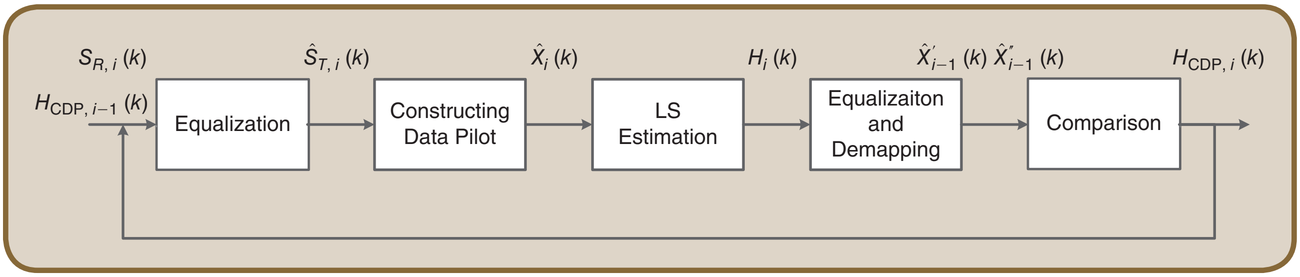

FIG 4 Schematic structure of the CDP estimator.

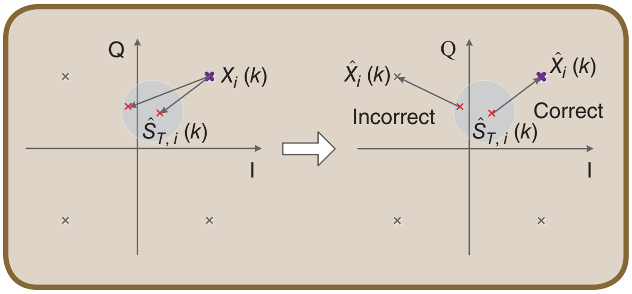

FIG 5 Principle of the CDP estimator ($i > 1$).

Step 3—LS Estimation

The constructed data pilot $\hat{X}_i(k)$ is then employed to calculate the ith data symbol's CR by using (3), i.e., the LS estimation. Note that $H_i(k)$ is a relatively accurate estimated CR, however, it is not the final output of the CDP estimator.

Step 4—Equalization and Demapping

In the following two steps, the high correlation characteristic is exploited again. $H_i(k)$ is first used to equalize $S_{R,i-1}(k)$ such that

$$\hat{S}'_{C,i-1}(k) = \frac{S_{R,i-1}(k)}{H_i(k)}. \tag{7}$$

$S_{R,i-1}(k)$ is then equalized by $H_{\mathrm{CDP},i-1}(k)$, i.e., the previous symbol's estimated CR, which has been used before in (6). The equalized $\hat{S}''_{C,i-1}(k)$ is given by

$$\hat{S}''_{C,i-1}(k) = \frac{S_{R,i-1}(k)}{H_{\mathrm{CDP},i-1}(k)}. \tag{8}$$

To compare $\hat{S}'_{C,i-1}(k)$ and $\hat{S}''_{C,i-1}(k)$ they should be demapped to the corresponding constellation points $\hat{X}'_{i-1}(k)$ and $\hat{X}''_{i-1}(k)$ according to the type of modulation.

Step 5—Comparison

As aforementioned, we have discussed that the two adjacent data symbols have high correlation. Hence, if $\hat{X}'_{i-1}(k) \neq \hat{X}''_{i-1}(k)$, it indicates that the kth subcarrier's $\hat{X}_i(k)$, which demapped after (6) is incorrect and we should define that $H_{\mathrm{CDP},i}(k) = H_{\mathrm{CDP},i-1}(k)$, i.e., the previous symbol's estimated CR. Otherwise, if $X'_{i-1}(k) = \hat{X}''_{i-1}(k)$, we have $H_{\mathrm{CDP},i}(k) = H_i(k)$.

It is noticeable that the condition for the previous channel estimation steps is $i > 1$ and $i = 1$ is excluded. The reason is that the two long training symbols are BPSK modulated to 1 and −1. However, data symbols are possibly modulated by other schemes instead of BPSK. Hence, (7) cannot be employed owing to the different modulation schemes. In addition, to ensure accuracy, the CR derived from (1) cannot be defined as $H_{\mathrm{CDP},1}(k)$ directly. Therefore, (7) should be modified to

$$\hat{S}'_{C,0}(k) = \mathrm{real}\left(\frac{R_{T_2}(k)}{H_1(k)}\right), \tag{9}$$

where $R_{T_2}(k)$ is the second long training symbol derived after FFT in the frequency domain. According to the property of the modulation scheme, if $\hat{S}'_{C,0}(k) > 0$, we have $\hat{X}'_0(k) = 1$ or else $\hat{X}'_0(k) = -1$. Note that, $\hat{X}''_0(k)$ is the known frequency-domain transmitted signal. Afterwards, $\hat{X}'_0(k)$ and $\hat{X}''_0(k)$ are compared with finally derive $H_{\mathrm{CDP},1}(k)$. If $\hat{X}'_0(k) = \hat{X}''_0(k)$, we have $H_{\mathrm{CDP},1}(k) = H_1(k)$; otherwise, we have $H_{\mathrm{CDP},1}(k) = H(k)$, where $H(k)$ is obtained from (1).

V. Simulation Results and Analysis

In this section, BER simulations are conducted. To compare with our proposed scheme, the LS and STA schemes are taken as two representative examples.

To achieve the optimal performance of the STA scheme, we set parameters $\alpha = \beta = 2$ as that in [11]. Figs. 6–11 show the comparison of the LS, STA, and CDP schemes in BER performance of QPSK and 16QAM under three vehicular environments, i.e., VTV Expressway Oncoming, RTV Urban Canyon, and VTV Urban Canyon Oncoming, respectively. To evaluate the performance of the IEEE 802.11p with different packet lengths, the numbers of OFDM symbols are chosen to be 100 and 200 for QPSK modulation, while 50 and 100 for 16QAM modulation. The figures depict that smaller packet length is beneficial for the BER performance, especially for STA and CDP schemes. As expected, the LS scheme keeps on a relatively high level of BER for both QPSK and 16QAM, while much smaller BERs are achieved by the STA and CDP schemes. When adopting high order modulation (e.g., 16QAM), The BER performance of the STA suffers from a severe degradation. In a very low SNR regime where the BER is around 0.5, STA scheme outperforms CDP scheme. When the SNR is high

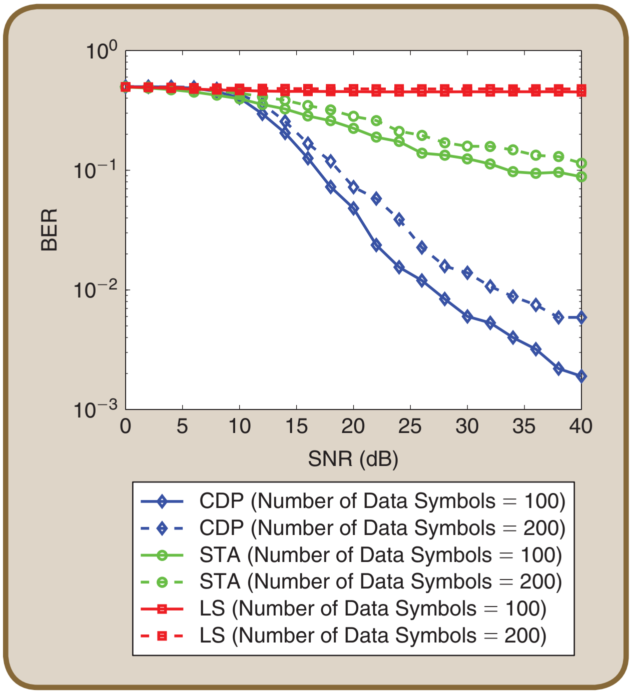

FIG 6 Comparison of the BER performance of the LS, STA, and CDP schemes in QPSK modulation (VTV expressway oncoming).

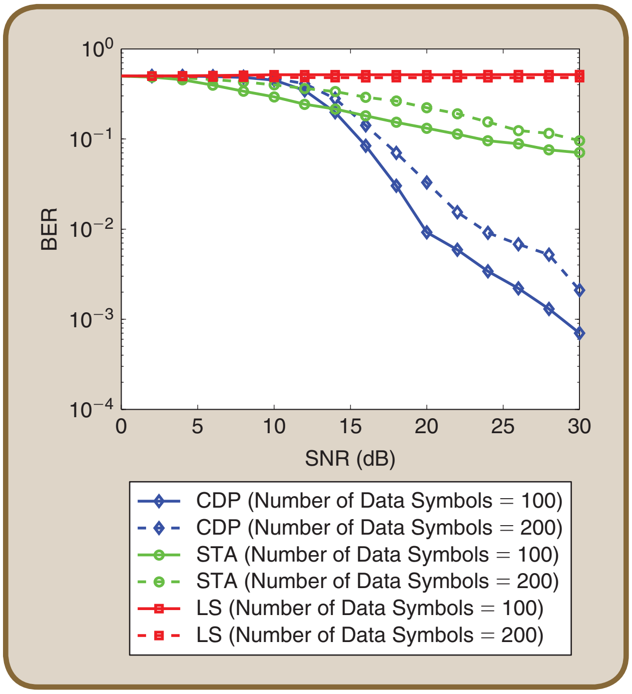

FIG 7 Comparison of the BER performance of the LS, STA, and CDP schemes in QPSK modulation (RTV urban canyon).

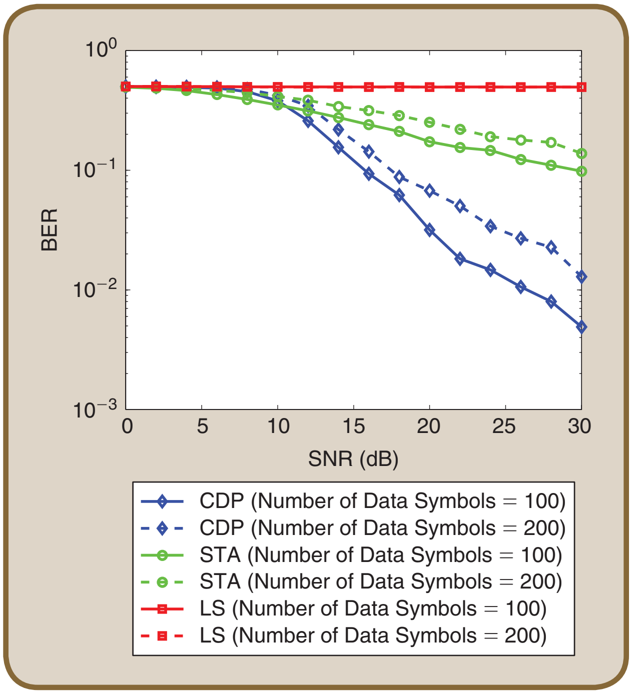

FIG 8 Comparison of the BER performance of the LS, STA, and CDP schemes in QPSK modulation (VTV urban canyon oncoming).

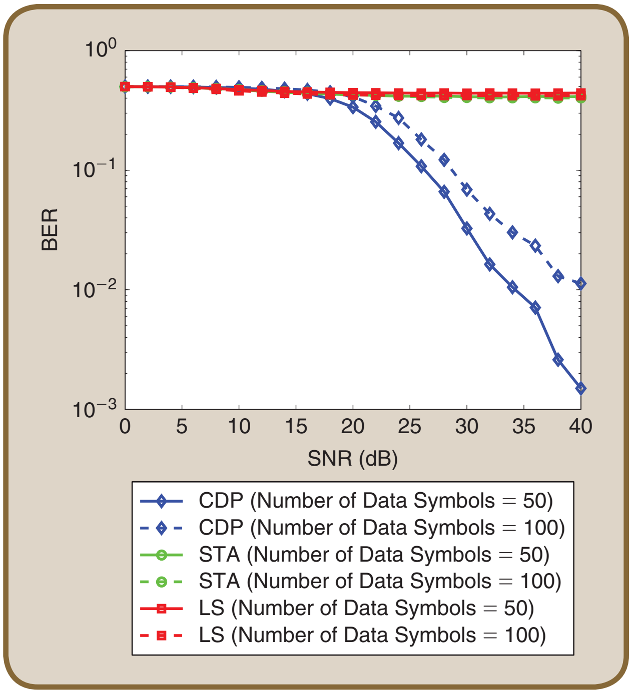

FIG 9 Comparison of the BER performance of the LS, STA, and CDP schemes in 16QAM modulation (VTV expressway oncoming).

enough, CDP scheme expresses a significant improvement over the STA scheme. This is because that when the SNR is low, the noise and interferences are powerful enough to shift $\hat{S}_{T,i}(k)$ to wrong regions and as a result, $\hat{X}_i(k)$ are demapped to incorrect constellation points. As the SNR increases, the aforementioned influence is reduced and thus the superiority of the CDP scheme emerges. According to the simulation, the smoothing in the frequency domain is not effective under vehicular environment. Hence for STA scheme, the error floor emerges in a relatively high

SNR regime. We remark that the impact from error demapping has been mitigated to a certain degree by the exploitation of the correlation characteristics of V2V channels.

To compare the BER performance under different vehicular environments, three representative scenarios are chosen. According to Table 2, the Doppler shift of VTV Expressway Oncoming, RTV Urban Canyon, and VTV Urban Canyon Oncoming scenarios are 1000–1200 Hz, 300 Hz, and 400–500 Hz, respectively. It is obvious that with higher Doppler shift, the V2V channels exhibit stronger time-varying characteristic. As for the RTV Urban Canyon scenario, which has the minimum Doppler shift, can reach 10^{-3} of the BER at a relatively lower SNR than the other two channels. Furthermore, with the increase of Doppler shift, CDP shows better performance at low SNR regime. The main reason is that the CDP algorithm is more appropriate for high Doppler shift due to the consideration of the correlation characteristics. While for the STA scheme, the average in the frequency domain offers an enhancement of performance at low SNR regime.

It is interesting to notice that although the VTV Expressway Oncoming scenario has higher Doppler shift (1000–1200 Hz) than VTV Urban Canyon Oncoming (Doppler shift 400–500 Hz), it outperforms the latter one. We cannot deny that high Doppler shift may degrade system performance, but besides, the following factors are also very critical, e.g., the traffic flow, the buildings nearby, and the locations of transmitter and receiver. In this case, the vehicles in VTV Urban Canyon Oncoming scenario are surrounded by buildings on roadside, which is unlike VTV Expressway Oncoming scenario where vehicles travel on the expressway with open environments. The channel condition of VTV Urban Canyon Oncoming scenario is degraded due to strong multipath effect caused by numerous reflections. Therefore, VTV Expressway Oncoming scenario exhibits better BER performance.

VI. Conclusions and Open Issues

In this article, we have focused on the channel estimation problem encountered in V2V communications. The issue is raised due to the inherent dynamic nature of V2V channels. The state-of-the-art of estimation technologies for V2V communications has been surveyed in this article. Although the current schemes may achieve considerable performance, there are still severe open challenges. To fill the gap, we have proposed a novel channel estimation scheme by constructing pilots using the data symbols and properly exploiting the correlation characteristics of V2V channels. Unlike most previous work, the proposed scheme adheres to the structure of the IEEE 802.11p standard and is independent on V2V channels. Therefore, the proposed scheme is not only compatible with other IEEE 802.11p receivers, but also applicable to different V2V scenarios. Simulation results have shown that the BER performance of the proposed scheme outperforms currently relevant schemes, e.g., STA scheme, especially in a high SNR regime. Furthermore, the proposed CDP scheme has the minimum computational complexity compared with the current estimation techniques for V2V channels, e.g., generalized DPS based scheme, decision-directed scheme, and pseudopilot scheme.

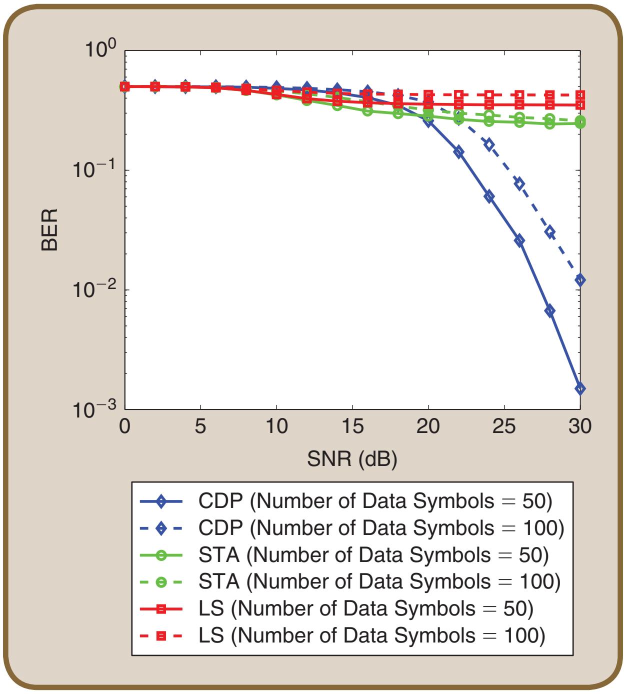

FIG 10 Comparison of the BER performance of the LS, STA, and CDP schemes in 16QAM modulation (RTV urban canyon).

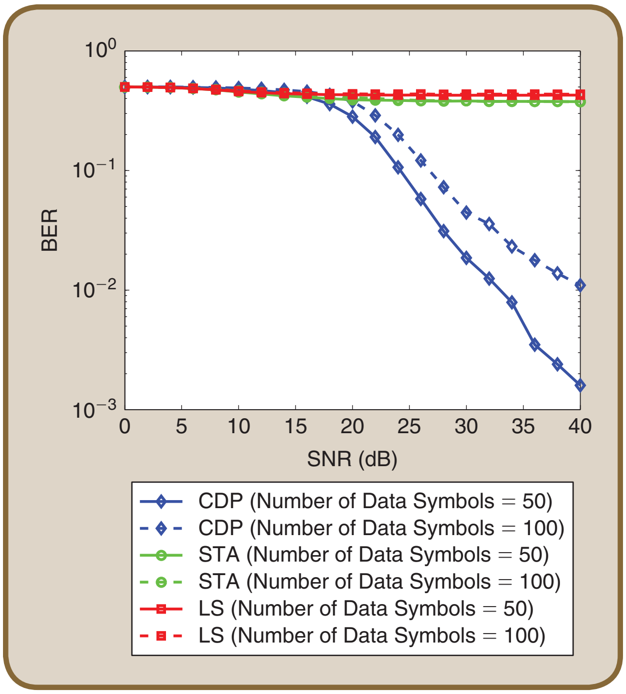

FIG 11 Comparison of the BER performance of the LS, STA, and CDP schemes in 16QAM modulation (VTV urban canyon oncoming).

Even if channel estimation techniques for V2V communications have been widely investigated, some improvements can still be achieved in the future work. Some open issues are presented below according to the current estimation techniques as well as the proposed scheme in this article.

1) Proper Utilization of Parameters Related to Channels

In Section III, the majority of the introduced channel estimation schemes need to know the channel information beforehand. It is evident that with the assist of necessary parameters related to channels, the performance can be further improved. However, these parameters related to channels are extremely hard to obtain in practice. Most current papers have not detailed how to derive those parameters or even not mentioned. For example, in [11], the parameters α and β, which represent time-variant and frequency-selective characteristics of the channel, are indispensable. The authors referred that these parameters are determined from GPS and map knowledge, which seems difficult to realize. As for vehicular environments, channel characteristics change rapidly due to high mobility and complex road conditions, therefore, exact values are really tough to obtain in practice. For further investigation, it is necessary to propose novel algorithms to derive these parameters or reduce the reliance on them.

2) Minimize the Computational Complexity

As surveyed before, most techniques, which belong to Manner 2, may achieve superior performance at the expense of very high computational complexity, e.g., [8], [10], and [12]. The high complexity of these schemes is mainly due to matrix multiplications. Though the work in [10] and [12] have introduced the improved algorithms, the performance will suffer from a degradation. From the perspective of hardware design, the approach, which has higher complexity, requires more hardware resource and thus wastes more energy. Therefore, we need to minimize the computational complexity, and meanwhile, ensure preferable performance. In this article, the proposed scheme has made an effort to minimize the computational complexity. However, the system performance of the proposed scheme can be further improved. For the current channel estimation techniques, a better manner to decrease the complexity is by exploiting channel characteristics and the properties of the IEEE 802.11p.

3) The Utilization of the Four Phase Tracking Pilots

According to the analysis in Section III, the four phase tracking pilots are too loosely placed to estimate the variation of channels in the frequency domain. Hence, generally speaking, the pilots in the IEEE 802.11p standard are not designed for channel estimation. The common manner for estimating vehicular channels is by exploiting the two long training symbols ahead of SIGNAL field as initial estimate, and then update the channel using data symbols. It is interesting that the surveyed work [8] has introduced a novel direction by virtue of pilots. Moreover, in [11], the pilots have also been used to provide averaging in the frequency domain. Even though the phase tracking pilots can hardly support reliable channel estimation alone, they may provide additional channel information for updating the channel. It is worth investigating in the future.

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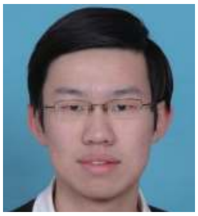

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