Guard Interval Assisted OFDM Symbol-Based Channel Estimation for Rapid Time-Varying Scenarios in IEEE 802.11p

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Keywords: IEEE 802.11p, Time-Varying Channel Estimation, OFDM, Vehicular-to-Vehicular Communication

Certificate

This is to certify that the thesis titled **"Guard Interval Assisted OFDM Symbol-Based Channel Estimation Techniques for Rapidly Time-Varying Scenarios in IEEE 802.11p"** submitted by **Priya Aggarwal** for the partial fulfillment of the requirements for the degree of *Master of Technology* in *Electronics and Communication & Engineering* is a record of the bonafide work carried out by her under our guidance and supervision at Indraprastha Institute of Information Technology, Delhi. This work has not been submitted elsewhere for the award of any other degree.

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Abstract

In the recent year, road accidents in India have drastically increased. Owing to this, there is a need for reliable and robust data transmission in vehicular communication. IEEE 802.11p standard is a dedicated wireless vehicular communication standard meant for outdoor applications. In this standard, one of the biggest challenges is robust channel estimation due to rapid time varying nature of the channel. The impact of channel interference on vehicular to-vehicular (V2V) communication fluctuates rapidly and unpredictably due to high mobility scenarios. However, IEEE 802.11p is developed without considering an impact of high mobility as it was originally derived from IEEE 802.11a standard, a standard meant for indoor applications. Thus, in this work, we are interested in estimating channel for V2V communication systems. We reviewed prior work on channel estimation in IEEE 802.11p standard and have made two significant research contributions:

First, we propose a novel decision-directed recursive least squares (RLS) time-domain channel estimation method that utilizes the guard interval (GI) of every orthogonal frequency division multiplexing (OFDM) symbol to track time-varying channel. Analysis and simulation results demonstrate that the proposed scheme outperforms existing GI assisted channel estimation schemes. Although, this proposed scheme suffers with inter carrier interference (ICI).

The second contribution of this work is even more significant. Here, we propose a new scheme that alleviates ICI in the previous proposed scheme. Proposed scheme utilizes the redundant space of GI (other than that required for cyclic prefix (CP) to combat ICI) to insert pseudo-random sequence (PRS) for channel estimation. A decision directed time-domain recursive least squares channel estimation method is proposed that utilizes the inserted PRS with CP. Simulation results show considerably improved bit error rate (BER) performance compared to the existing methods. Thus, proposed scheme enables robust channel equalization in rapidly time-varying channel with high Doppler spread.

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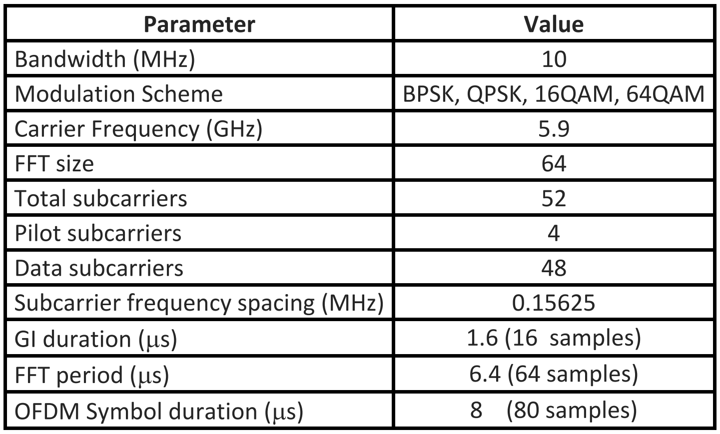
Chapter 1

Introduction

Every year 1.24 million people lose their lives worldwide due to accidents on road [1]. Road traffic safety can be substantially improved with the help of wireless vehicular communication, e.g., via warnings for abrupt vehicle kinetic changes, traffic and road conditions, etc. [2, 3]. Hence, there is an increasing need of reliable data transmission. To meet this requirement in wireless vehicular communication, IEEE 802.11p [4], a dedicated standard for wireless access in vehicular environments (WAVE), has been standardized in 2010. Table 1 shows the physical parameter of IEEE 802.11p.



Parameter	Value
Bandwidth (MHz)	10
Modulation Scheme	BPSK, QPSK, 16QAM, 64QAM
Carrier Frequency (GHz)	5.9
FFT size	64
Total subcarriers	52
Pilot subcarriers	4
Data subcarriers	48
Subcarrier frequency spacing (MHz)	0.15625
GI duration (µs)	1.6 (16 samples)
FFT period (µs)	6.4 (64 samples)
OFDM Symbol duration (µs)	8 (80 samples)

Table 1.1: Physical parameters of IEEE 802.11p

Compared to other wireless local area network (WLAN) standards such as IEEE 802.11a/g [4], this standard is meant for dedicated short range communications (DSRC) between vehicular-to-vehicular (V2V) and vehicular-to-infrastructure (V2I) or (I2V) scenarios. It supports many intelligent transport system (ITS) applications such as cooperative safety, smooth traffic flow, accident control, intersection collision avoidance, emergency warning, etc. [2].

Fig. 1.1 shows the OFDM frame structure. An OFDM frame starts with a short preamble (of 16μs) that is used for start of frame detection and, coarse time and frequency synchronisation [5].

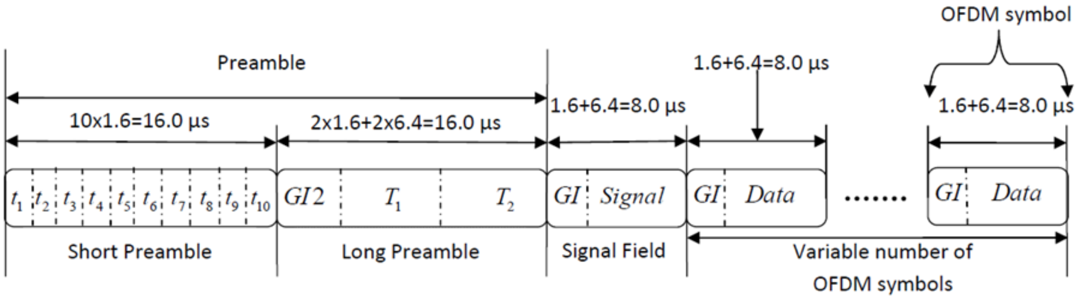


Figure 1.1: OFDM Frame Structure

It is followed by long preamble (of 16μs) that is used for fine time-synchronisation and channel estimation. Signal field of the frame contains information about modulation and coding. This is followed by variable number of OFDM symbols. In general, number of OFDM symbols can be chosen according to the coherence time of the channel.

1.1 Motivation of the thesis

In V2V communication, channel changes rapidly due to high mobility scenarios. To this end, a dedicated standard IEEE 802.11p has been adopted. This standard modifies 802.11a/g standard in order to add support for WLANs in a vehicular environment. However, for channel tracking there is no amendment in this standard. Notably, guard interval (GI) duration in the IEEE 802.11p standard is doubled in comparison to the IEEE 802.11a standard, so as to support severe multipath delay spread of the vehicular channel. Although, severe multipath delay spread may not be as significant a problem as fast time varying nature of channel in vehicular environment. Thus, this standard is not yet well adapted for the fast time varying channel conditions [6]. In the present wireless vehicular communication, there is a increasing need of robust channel estimation which helps in reliable transmitted data recovery at the receiver.

This motivated us to look deeper into channel estimation methods in IEEE 802.11p, and propose robust methods to track fast time varying channel.

The purpose of this thesis is to develop methods for estimating rapidly time varying channel in IEEE 802.11p. Accurate channel estimation is critical for the follow-up robust equalization and demodulation of transmitted data at the receiver end. Thus, a robust channel estimation method is needed at the receiver end for 802.11p standard to alleviate the impact of rapid vehicular motion.

1.2 Outline

Following an introduction, the reminder of the thesis is organized as follows.

Chapter 2 This chapter briefly presents literature review on channel estimation methods in IEEE 802.11p and discuss limitations of these existing methods.

Chapter 3 This chapter describes the proposed recursive least square with decision directed (RLSwDD) channel estimation method.

Chapter 4 This chapter describes the proposed OFDM transceiver structure related channel estimation method in IEEE 802.11p standard.

Chapter 5 This chapter concludes the thesis and suggests the possible directions for future work.

Chapter 2

Overview of Current Channel Estimation Schemes

Conventional channel estimation methods inherently assume channel to be stationary in one OFDM frame and hence, use long preamble inserted in every OFDM frame for channel estimation. However, during rapid time-varying channel conditions (or high speed V2V communication), the coherence time may reduce considerably causing channel to vary within one OFDM frame that may consist of many OFDM symbols. Hence, the channel estimates obtained using long preamble may not be valid for all of the OFDM symbols within a frame leading to severe ISI and abysmal performance in fast time varying channels [7].

In view of this aspect, pilot data inserted within an OFDM symbol can be used for fine tuning of an estimated channel. However, pilot density in IEEE 802.11p is not sufficient to compensate for time varying nature of the channel, especially, in the urban environment where time selectivity and Doppler spread of the channel may be high.

Apart from the use of long preamble and pilots, lot of channel estimation schemes have been proposed for 802.11 standards. However, all efforts are directed with an assumption of stationary channel. Thus, most of them will not be applicable for 802.11p due to this fast time varying nature of the channel.

To address these limitations, researchers have proposed various methods to estimate time varying channel in IEEE 802.11p standard. We briefly describe existing prior methods of channel estimation in IEEE 802.11p standard and discuss their limitations as below:

1. Pseudo-pilot channel estimation scheme

   In [8], pilot density is increased with the insertion of pseudo pilots. The long preamble first provides a crude channel estimation and the denser pilot symbols are then utilized to track time varying channel. It is obvious that with pseudo pilots, the efficiency of channel estimation is enhanced. However, this method reduces transmission throughput. Thus, it degrades the performance in terms of reduced data payload capacity.

2. Midamble based channel estimation scheme

   Recently, in [9] authors have proposed a midamble based approach wherein a known midamble data is inserted between OFDM symbols of an OFDM frame, to track the channel in IEEE 802.11p standard. The midambles are inserted periodically in an OFDM frame. First, the channel is estimated by long preamble. Consequently, subsequent data symbols are equalised with an initial estimated channel by long preamble, until the occurrence of first midamble. This procedure keeps on repeating until the next midamble provides the channel update. However, this approach degrades the performance in terms of availability of less data payload and hence, lowers the transmission rate.

3. Time domain least squares estimation (TDLSE) scheme

   In [10, 11], authors used guard interval (GI) for time domain channel estimation by replacing the cyclic prefix by pseudo-random sequence with zero padding (PRwZP). Specifically, in [10], time domain least squares method (TDLSE) is proposed for channel estimation (PRwZP TDLSE scheme). Channel is estimated in the beginning of every OFDM symbol. However, due to omission of cyclic prefix in the GI, it suffers with the problem of inter-carrier interference (ICI).

4. Time domain least squares with overlap-and-add (TDLSE w/OLA) method

   In [11], the problem of ICI is alleviated by using the overlap-and-add method (OLA) in conjunction with PRwZP TDLSE scheme. Notably, ICI is cancelled in OLA only when the channel is time-invariant during one OFDM frame. Thus, this method is not appropriate to combat ICI in the TDLSE scheme.

5. Time domain least squares with smoothing (TDLSE w/smooth) scheme

   A smoothing based PRwZP TDLSE OLA scheme is also presented in [11] that utilizes past and future OFDM symbols. However, smoothing estimation will introduce delays in the case of real-time environments and the performance will deteriorate if the channel changes within the smoothing window duration.

2.1 Conclusion

Although the aforementioned channel estimation schemes are able to track time varying channel in some cases, they still have some limitations. In order to improve reliable data transmission in the V2V communication, there is an increasing quest for the development of methods for tracking fast time varying channel.

Chapter 3

Recursive Least Square Channel Estimation

3.1 Overview

We notice that although it is encouraging to use TDLSE based schemes [10, 11] for channel estimation in every OFDM symbol, it suffers with some limitations such as

a) The smoothing method appears prohibitive in real-time applications because of delay.

b) Computation of inversion in least squares (LS) introduces additional computational time for every OFDM symbol.

In order to overcome these limitations, we propose a novel time-domain recursive least squares (RLS) channel estimation method with decision directed approach in the GI of every OFDM symbol. The RLS algorithm requires computations of the order of $O(N^2)$ compared to LS that requires computations of the order of $O(N^3)$ [12]. Thus, it brings down the computational time complexity. Also, we add decision-directed approach that utilizes the data sample estimates of previous OFDM symbol and improves performance over all existing GI assisted channel estimation methods.

Below are the contributions of the proposed algorithm:

1. Proposed scheme guarantees better performance for time-varying channel estimation compared to the existing techniques due to the proposed decision-directed approach.
2. Proposed adaptive RLS algorithm is computationally less time-intensive compared to the existing LS based algorithms.

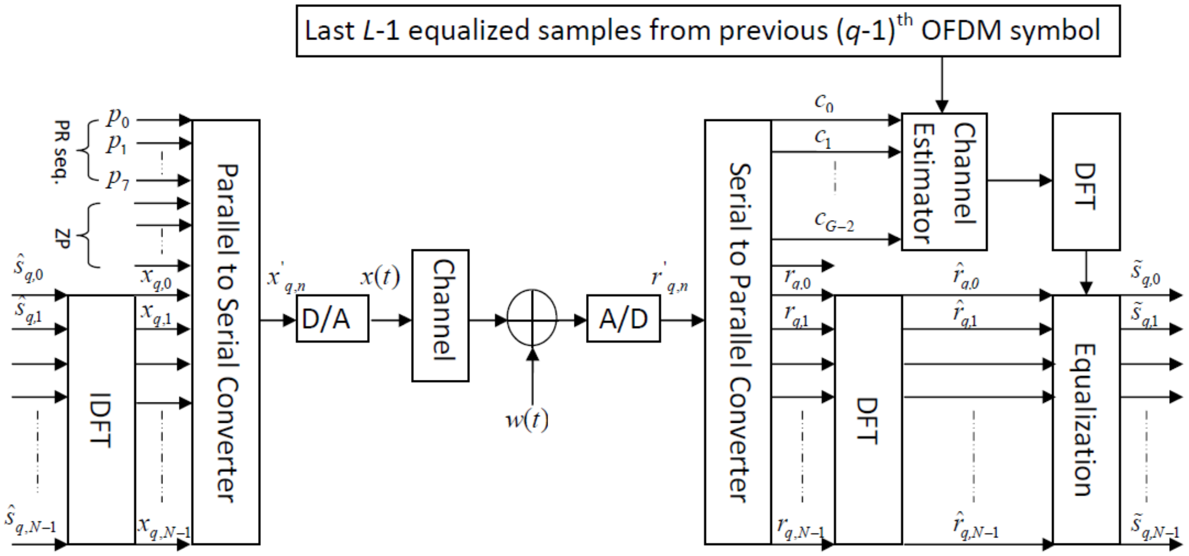


Figure 3.1: OFDM Symbol Transceiver Structure

3.1.1 OFDM transceiver structure

The transceiver structure discussed in this section is identical to that proposed in [10] and [11]. Fig. 3.1 shows the OFDM transceiver structure for the q^{th} OFDM symbol. First G (=16) samples of every OFDM symbol correspond to the guard interval (GI), while the last N (=64) samples denoted as $\{\hat{s}_{q,0}, \hat{s}_{q,1}, \cdots, \hat{s}_{q,N-1}\}$ correspond to the complex data samples to be transmitted in the frequency domain where the subscript q corresponds to the q^{th} OFDM symbol. This data is passed through the inverse Discrete Fourier Transform (IDFT) block to obtain time domain complex data samples as

$$x_{q,n} = IDFT_N\left(\hat{s}_{q,k}\right) \quad \text{for} \quad n, k = 0, 1, \cdots, N-1. \tag{3.1}$$

where n and k are indices in time and frequency domain, respectively. We insert a pseudo-random (PR) sequence $\{p_0, p_1, \cdots, p_7\}$ of length $L_p = 8$ and zero padding (ZP) of length 8 in the guard interval of every OFDM symbol. Thus, the resultant data which is to be transmitted, in an OFDM symbol is:

$$x'_{q,n} = \begin{cases} p_n & n = 0, 1, \cdots, 7 \\ 0 & n = 8, 9, \cdots, G-1 \\ x_{q,n-G} & n = G, \cdots, N+G-1 \end{cases} \tag{3.2}$$

Symbols $x'_{q,n}$ are serially fed to a D/A converter and the resultant signal $x(t)$ is transmitted. The transmitted signal is passed through a time-varying multipath fading channel and is corrupted by white Gaussian noise. The A/D converter at the receiver converts this noisy analog information back into serial digital information which is denoted by:

$$r'_{q,n} = \{c_0, c_1, \cdots, c_{L_p+L-2}, \mathbf{0}_{1\times L_p-L+1}, r_{q,0}, r_{q,1}, \cdots, r_{q,N-1}\} \tag{3.3}$$

where $c_0, c_1, \cdots, c_{L_p+L-2}$ are the first L_p+L-1 time domain recieved samples and L corresponds to the maximum channel delay spread of Lx duration of each tap (or L-tap multipath fading channel). We utilize the first $L_p + L - 1$ time domain samples for channel estimation. Details on the proposed channel estimation method are presented in section 3.2.

First $L_p + L - 1$ time domain samples of $r'_{q,n}$ can be represented as

$$c = \begin{cases} \sum_{i=0}^{n} h_i p_{n-i} + \sum_{i=n+1}^{L-1} h_i x_{q-1,n+N-i} + w_{q,n} \\ \qquad\qquad \text{for} \quad n = 0, 1, \cdots, L-2 \\ \\ \qquad\qquad \sum_{i=0}^{L-1} h_i p_{n-i} + w_{q,n} \\ \qquad \text{for} \quad n = L-1, L, \cdots, L_p + L - 1 \end{cases} \tag{3.4}$$

where $\{h_0, h_1, \cdots, h_{L-1}\}$ are the channel tap coefficients, $x_{q-1,N-1}$ is the $(N-1)^{th}$ sample of the $(q-1)^{th}$ OFDM symbol, and $w_{q,n}$ is the complex white Gaussian noise.

The last N time domain samples of $r'_{q,n}$ are fed to the Discrete Fourier Transform (DFT) block. The resultant output in the frequency domain is denoted as $\hat{r}_{q,k}$ where $k = 0, 1, ..., N-1$.The estimated channel tap coefficients are denoted as $\tilde{h}_0, \tilde{h}_1, \cdots, \tilde{h}_{L-1}$ and the N-point DFT of the estimated channel tap coefficients are denoted as $\hat{h}_{q,k} = DFT_N\left(\tilde{h}_0, \tilde{h}_1, \cdots, \tilde{h}_{L-1}, 0, 0, \cdots, 0\right)$. Zero forcing channel equalization algorithm is used to estimate the transmitted frequency domain data samples [13] as below

$$\tilde{s}_{q,k} = \hat{r}_{q,k}/\hat{h}_{q,k} \quad \text{for} \quad k = 0, 1, \cdots, N-1. \tag{3.5}$$

3.2 Proposed RLS based Decision-Directed Channel Estimation Method

A robust channel estimation algorithm should be able to track rapid time varying channel. In this paper, we utilize the pseudo-random sequence inserted with ZP (PRwZP) in the GI for channel estimation in every OFDM symbol.

The first $L_p + L - 1$ received time domain samples of $r'_{q,n}$ after A/D conversion denoted in (3.4) can be written as

$$\mathbf{c} = \mathbf{M}\mathbf{h} + \mathbf{w} \tag{3.6}$$

where $\mathbf{c} = \left[c_0, c_1, \cdots, c_{L_p+L-2}\right]^T$, $\mathbf{w}$ is the vector of complex baseband additive white Gaussian noise (AWGN) that is assumed to be uncorrelated with the channel $\mathbf{h}$ and

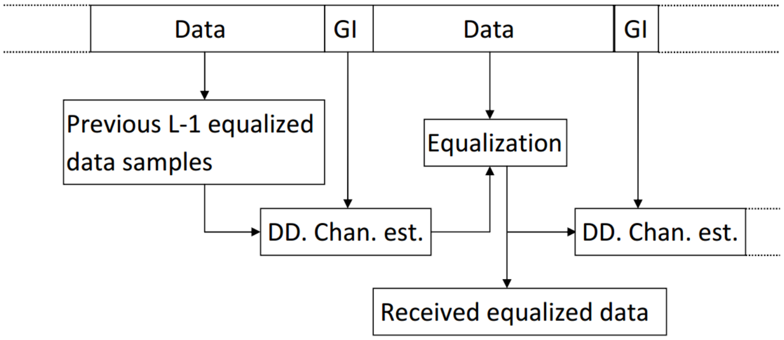


Figure 3.2: Block Diagram of the Proposed Channel Estimation Method

$$\mathbf{M} = \begin{bmatrix} p_0 & x_{q-1,N-1} & \cdots & x_{q-1,N-L+2} & x_{q-1,N-L+1} \\ p_1 & p_0 & \ddots & \vdots & \vdots \\ p_2 & p_1 & \ddots & p_0 & x_{q-1,N-1} \\ \vdots & \vdots & \ddots & \vdots & p_0 \\ \vdots & \vdots & \ddots & p_7 & \vdots \\ 0 & 0 & \cdots & 0 & p_7 \end{bmatrix}_{(L_p+L-1)\times L}$$

where $x_{q-1,N-1}$ is the $(N-1)^{th}$ data sample of the previous $(q-1)^{th}$ OFDM symbol.

This is to note that the first $L-1$ rows of matrix $\mathbf{M}$ contain the last $L-1$ data samples of the previous OFDM symbol. Since these data samples of the previous OFDM symbol have already been estimated, the use of the estimated samples in the channel estimation during the current OFDM symbol makes the scheme decision-directed. This proposed solution of channel estimation is labeled as RLS w/DD time-domain channel estimation (RLS w/DD). The proposed channel tracking scheme is illustrated with block diagram in Fig. 3.2.

With the availability of the PR training sequence and the estimates of $\{\hat{x}_{q-1,N-1}, \hat{x}_{q-1,N-2}, \cdots, \hat{x}_{q-1,N-L+1}\}$ from the previous OFDM symbol, the matrix $\mathbf{M}$ is estimated as $\tilde{\mathbf{M}}$ at the receiver during the GI of the current OFDM symbol. Recursive least squares solution of (3.6) minimizes the total squared error, $E(j)$ at any time instant j given as

$$E(j) = \sum_{i=0}^{j} |c(i) - \mathbf{M}(i,:)\mathbf{h}(i)|^2 \tag{3.7}$$

and provides the solution at time index j as below [14]:

$$\tilde{\mathbf{h}}(j) = \hat{\mathbf{R}}^{-1}(j)\hat{\mathbf{d}}(j) \quad \text{for} \quad j = 0, 1, \cdots, L_p + L - 1. \tag{3.8}$$

where $\tilde{\mathbf{h}}(j)$ is the estimated channel tap coefficient vector $[\tilde{h}_0, \tilde{h}_1, \cdots, \tilde{h}_{L-1}]^T$ in the current OFDM symbol and, $\hat{\mathbf{R}}(j)$ and $\hat{\mathbf{d}}(j)$ are given as:

$$\hat{\mathbf{R}}(j) = \sum_{i=0}^{j} \lambda^{j-i} (\tilde{\mathbf{M}}(i,:))^H \tilde{\mathbf{M}}(i,:) \tag{3.9}$$

and

$$\hat{\mathbf{d}}(j) = \sum_{i=0}^{j} \lambda^{j-i} (\tilde{\mathbf{M}}(i,:))^H c(j) \tag{3.10}$$

where λ is the forgetting factor with the range $0 < \lambda < 1$. In the RLS algorithm, $\hat{\mathbf{R}}(j)$ and $\hat{\mathbf{d}}(j)$ are updated iteratively as

$$\hat{\mathbf{R}}(j) = \lambda \hat{\mathbf{R}}(j-1) + (\tilde{\mathbf{M}}(j,:))^H \tilde{\mathbf{M}}(i,:) \tag{3.11}$$

$$\hat{\mathbf{d}}(j) = \lambda \hat{\mathbf{d}}(j-1) + (\tilde{\mathbf{M}}(i,:))^H c(j) \tag{3.12}$$

Since matrix inversion is time-intensive, calculation of $\hat{\mathbf{R}}^{-1}(j-1)$ in (3.8) adds more time-complexity to the RLS solution. Thus, $\hat{\mathbf{R}}^{-1}(j-1)$ required in equation (3.8) is also updated iteratively as below:

$$\hat{\mathbf{R}}^{-1}(j) = \lambda \hat{\mathbf{R}}^{-1}(j-1) - \alpha(j)\mathbf{g}(j)\mathbf{g}^H(j) \tag{3.13}$$

where

$$\mathbf{g}(j) = \lambda^{-1} \hat{\mathbf{R}}^{-1}(j-1)(\tilde{\mathbf{M}}(j,:))^H \tag{3.14}$$

and

$$\alpha(j) = 1 + \tilde{\mathbf{M}}(j,:)\mathbf{g}(j) \tag{3.15}$$

On using the above equations in (3.8), RLS update equation for channel tap coefficients is given as [14]:

$$\tilde{\mathbf{h}}(j) = \tilde{\mathbf{h}}(j-1) + \frac{\mathbf{g}(j)e(j)}{\alpha(j)} \tag{3.16}$$

where

$$e(j) = c(j) - \tilde{\mathbf{M}}(j,:)\tilde{\mathbf{h}}(j-1) \tag{3.17}$$

In RLS channel tap coefficients are updated recursively upon receiving the new training sample. RLS is used when data samples are received sequentially and the estimated coefficients are required to be updated with the arrival of new measurements. Utilizing this method for channel estimation in time varying environment requires no a-priori knowledge of channel statistics. For the simulation, initial estimate of λ and $\hat{\mathbf{R}}^{-1}(0) = \frac{\mathbf{I}_{L\times L}}{\epsilon}$ are chosen empirically with λ=0.995 and $\epsilon = 10^{-3}$ [15].

3.3 Simulation Results

In this section, we present simulation results to validate the working of the proposed channel estimation algorithm. Simulation results are carried out via the transmission of 100 OFDM frames over 500 channel realizations and 200 noise realizations. The number of OFDM symbols per frame is chosen to be 10 and 64, respectively. Data is modulated via quadrature phase-shift keying (QPSK). Results are generated with channel coherence times of 120μs (equal to

15 OFDM symbol duration) and 552μs (equal to 69 OFDM symbol duration). We simulated data communication via IEEE 802.11p standard for two wireless channel models (as shown in Table-3.1) of DSRC [16]. We used tapped delay line model for generating channel taps with the desired power spectrum profile as shown in Table-3.1. We generated each tap after 100ns delay. Maximum channel delay spread is 700ns for the 8-tap channel model and 400ns for the 5-tap channel model, respectively.

In the case of V2V communication, it has been observed that maximum channel taps can be 8-10 [16-19]. Although channel can have longer delay spread, there is sufficient power in only fewer taps. In general, results have been shown in the literature with only 3-7 tap length channels [16-19]. We have shown simulations over 5 tap (common for V2V) and 8-tap channels. Thus, we can easily fix the length of PR sequence to be 8 ($=Lp$). This provides us matrix $\mathbf{M}$ in (3.6) of maximum size ($Lp + L - 1 = 16$) x L with maximum channel length to be 9.

In order to assess the un-coded performance of the proposed channel estimation scheme, no error correction codes are used in the simulation. Perfect timing synchronisation is assumed at the receiver end. In this section, we compare the performance of PRwZP TDLSE and its variants [10, 11] and the proposed PRwZP RLS w/DD scheme with reference to Bit Error Rate (BER) versus energy per bit to noise power spectral density (E_b/N_0). In order to assess the performance of the decision-directed scheme, we have also shown results of PRwZP RLS (i.e., without decision-directed) scheme.

Fig.-3.3 and Fig.-3.4 show the simulation results for channel model-1 (8-tap) under the channel coherence times of 120μs and 552μs, respectively. Similarly, Fig.-3.5 and Fig.-3.6 show the simulation results for channel model-2 (5-tap) under the channel coherence times of 120μs and 552μs, respectively. From these figures, the following observations are in order:

1. The proposed RLS and RLS w/DD schemes work better than the existing schemes that utilize LS for channel estimation.
2. Number of channel taps affects the performance of the proposed algorithm. For the 5-tap channel model, BER obtained is much closer to that of perfect channel state information (CSI). Thus, maximum excess delay spread of the channel impacts the performance of the proposed system.
3. In the case of PRwZP, orthogonality among subcarriers is lost. Although the existing PRwZP TDLSE with OLA is able to overcome this problem, the performance of RLS w/DD is even better than this. This shows that decision-directed scheme is able to mitigate the effect of ISI and ICI better than the OLA scheme.
4. Smoothing based techniques will fail when the channel varies within the smoothing window. Also, large smoothing windows will introduce longer delays that may be undesirable in real-time operations. The proposed algorithm works better than the smoothing based TDLSE method.

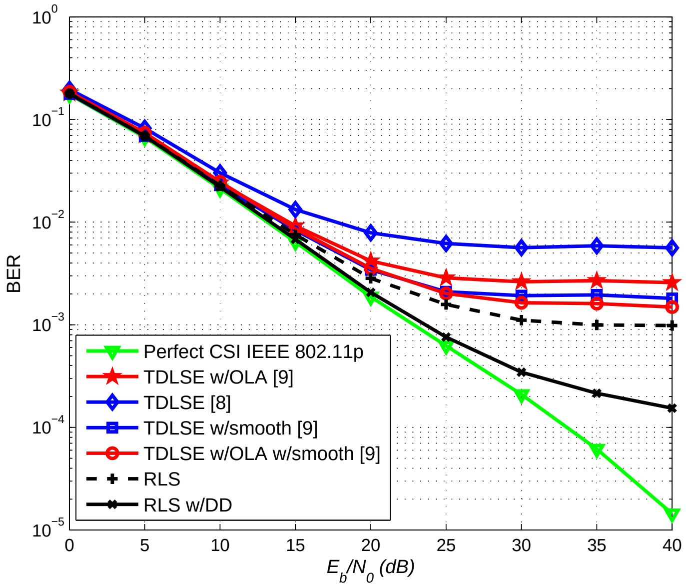


Figure 3.3: BER vs. E_b/N_0, coherence time 120μs, 10 OFDM symbol per frame, 8-tap channel model (Channel-1), 120 km/h

5. Simulation results show that the proposed algorithm provides the best performance (very close to perfect channel state information (CSI)) compared to the existing GI based channel estimation methods.

Tap	Time (ns)	**Channel-1** Suburban street (120 km/h)	**Channel-2** Expressway (140 km/h)
1	0	0.0 dB, Rician, K = 3.3 dB	0.0 dB, Rician, K =−5.3 dB
2	100	−9.3 dB, Rayleigh	−9.3 dB, Rayleigh
3	200	−14.0 dB, Rayleigh	−20.3 dB, Rayleigh
4	300	−18.0 dB, Rayleigh	−21.3 dB, Rayleigh
5	400	−19.4 dB, Rayleigh	−28.8 dB, Rayleigh
6	500	−24.9 dB, Rayleigh	0
7	600	−27.5 dB, Rayleigh	0
8	700	−29.8 dB, Rayleigh	0

K = ratio of the specular to diffuse component power of the received signal

Table 3.1: Parameters of vehicular channel models

3.4 Conclusion

In this chapter, a novel time domain decision directed channel estimation based on RLS is proposed for rapid time varying channel estimation in IEEE 802.11p. The computationally complexity is significantly reduced by recursively updating the channel on an arrival of new sample and with no matrix inversion. Due to the inclusion of decision-directed scheme in the proposed method, the channel estimation method is able to mitigate the effect of ISI and ICI with no overhead of midamble insertion. Moreover, the proposed method does not require

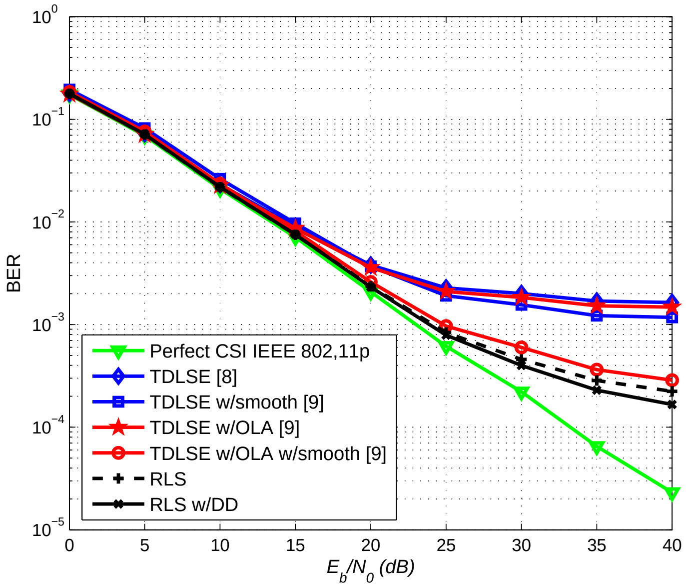


Figure 3.4: BER vs. E_b/N_0, coherence time 552μs, 64 OFDM symbol per frame, 8-tap channel model (Channel-1), 120 km/h

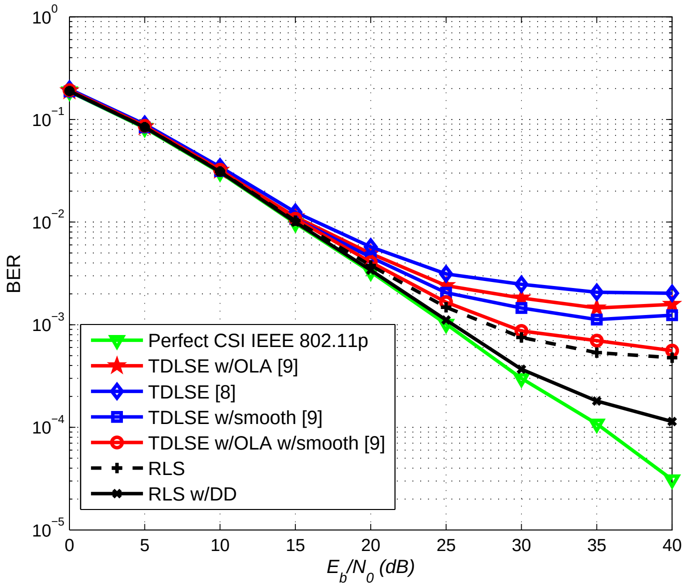


Figure 3.5: BER vs. E_b/N_0, coherence time 120μs, 10 OFDM symbol per frame, 5-tap channel model (Channel-2), 140 km/h

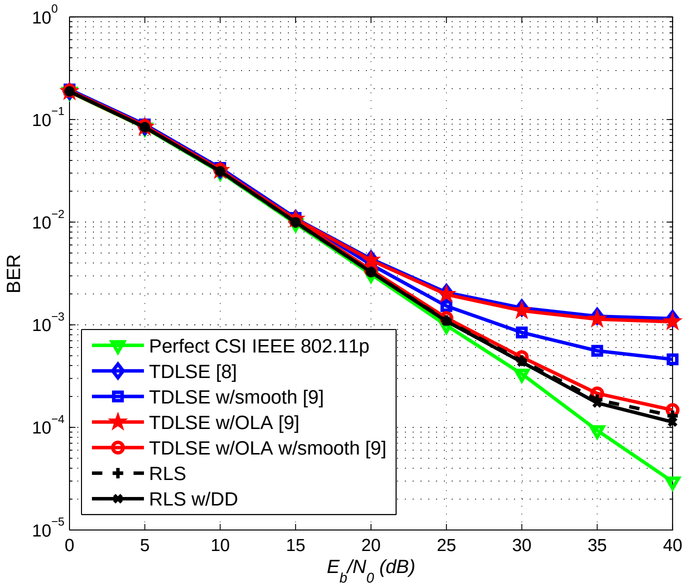


Figure 3.6: BER vs. E_b/N_0, coherence time 552μs, 64 OFDM symbol per frame, 5-tap channel model (Channel-2), 140 km/h

channel estimation via preamble and hence, effective data rate can be increased via removal of preamble in the future standards. This can address higher wireless data rate challenge for 5G communication.

Chapter 4

Proposed OFDM Transceiver based Channel Estimation Method

4.1 Overview

Although, proposed computationally less time-intensive RLS w/DD channel estimation scheme guarantees better performance for time varying channel estimation compared to existing techniques, it suffers with the problem of ICI. Thus, to alleviate ICI, we propose a novel GI assisted channel estimation method and overcome the above limitation via the following proposed modification:

- We insert short pseudo-random sequence along with cyclic prefix (PRwCP OFDM) instead of replacing the entire guard interval (GI) with the pseudo-random sequence.

In the IEEE 802.11p standard, length of GI is fixed. We are not proposing to increase/decrease the length of GI. But we propose to make use of the portion of GI other than that required for CP for additional work (i.e. to estimate a fast fading channel).

The merits of the proposed channel estimation method are that it

a) does not suffer with reduced throughput via midamble insertion;

b) does not suffer with ISI due to cyclic prefix and ICI (as it correctly estimates fast fading channel);

c) does not require channel estimation via long preamble and hence, effective data rate can be increased via removal of long preamble. This may be useful in addressing higher wireless data rate challenge of 5G communication [20]; and

d) does not require smoothing operation and hence, provides real-time channel estimation with improved performance over channel varying as fast as over one symbol duration.

4.2 Proposed PRwCP OFDM Transceiver Structure

Consider Fig. 4.1 that shows the structure of the proposed PRwCP transceiver for the m^{th} OFDM symbol. First 16 samples of every OFDM symbol correspond to the GI, while the last N=64 samples denoted as $\{\hat{s}_{m,0}, \hat{s}_{m,1}, \cdots, \hat{s}_{m,N-1}\}$ correspond to the complex data samples to be transmitted in the frequency domain. This data is passed through the inverse discrete Fourier transform (IDFT) block to obtain time domain complex data samples as

$$s_{m,n} = IDFT_N \left(\hat{s}_{m,k}\right) \tag{4.1}$$

where $n = 0, 1, \cdots N - 1$ and $k = 0, 1, \cdots N - 1$.

In the proposed work, for length L channel, a cyclic prefix (CP) of length L-1 (the last L-1 time domain samples $s_{m,n}$ of the m^{th} OFDM symbol) and a pseudo-random (PN) sequence of length D $\{p_0, p_1, \cdots, p_{D-1}\}$ are inserted in the guard interval of m^{th} OFDM symbol. Thus, the resultant data in an OFDM symbol is:

$$s'_{m,n} = \begin{cases} p_n & n = 0, 1, \cdots, D-1 \\ s_{m,n+N-16} & n = D, D+1, \cdots, D+L-2 \\ s_{m,n-16} & n = D+L-1, \cdots, D+L+N-2 \end{cases} \tag{4.2}$$

where $D = 16 - L + 1$ with L corresponds to the length of multipath fading channel and $D + L + N - 1 = 80$ (length of one OFDM symbol).

Our proposed scheme first fixes the length of CP required to combat ISI. Since the number of channel taps presumably will be fewer in the case of fast fading scenario, the required cyclic prefix (CP) in the guard interval (GI) to combat ISI will be less. For example, say the length of channel is 8. The required length of CP is 7. But the GI has 16 sample space. So, we are proposing to use the remaining samples 16-7=9 for channel estimation by inserting the pseudo random sequence (PRS).

Symbols $s'_{m,n}$ are serially fed to a D/A converter and the resultant signal $s(t)$ is transmitted. The transmitted signal is passed through a time-varying multipath fading channel and is corrupted by white Gaussian noise. The A/D converter at the receiver converts this noisy analog information back into serial digital information which is denoted by $r'_{m,n}$ as:

$$\begin{aligned} r'_{m,n} = &\{c_0, c_1, \cdots, c_{D-1}, r_{m,N-L+1}, r_{m,N-L+2}, \cdots, \\ & r_{m,N-1}, r_{m,0}, \cdots, r_{m,N-1}\} \end{aligned} \tag{4.3}$$

The last N time domain samples of $r'_{m,n}$ are fed to the discrete Fourier transform (DFT) block. The resultant output in the frequency domain is denoted as $\hat{r}_{m,k}$ where $k = 0, 1, \cdots, N-1$. We utilize the first D time domain symbols of $r'_{m,n}$ for channel estimation. A detailed explanation on channel estimation is provided in section 4.3. The estimated channel tap coefficients are denoted as $\tilde{h}_0, \tilde{h}_1, \cdots, \tilde{h}_{L-1}$ and the N-point DFT of the estimated channel tap coefficients are denoted

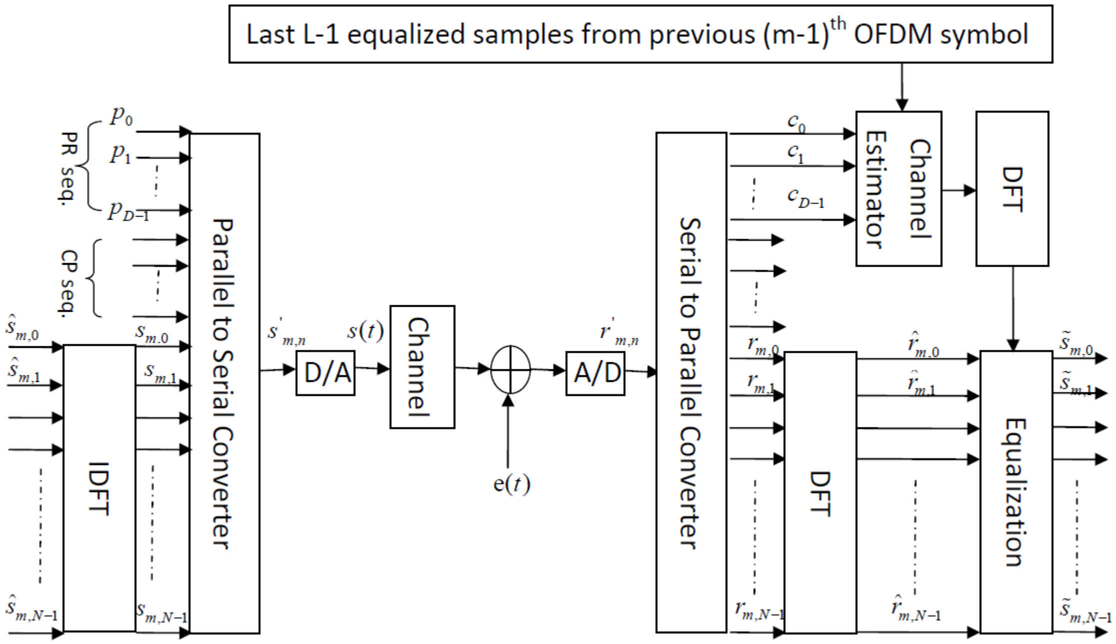


Figure 4.1: Proposed PRwCP OFDM Transceiver Structure

as $\hat{h}_{m,k} = DFT_N\left(\tilde{h}_0, \tilde{h}_1, \cdots, \tilde{h}_{L-1}, 0, 0, \cdots, 0\right)$. Zero forcing channel equalization algorithm is used to estimate the transmitted frequency domain OFDM symbol as below [13]:

$$\tilde{s}_{m,k} = \hat{r}_{m,k}/\hat{h}_{m,k} \quad \text{for} \quad k = 0, 1, \cdots, N-1. \tag{4.4}$$

4.3 Decision Directed Channel Estimation

In the case of rapid time-varying channel, channel coefficients change within the OFDM frame. A robust channel estimation algorithm should be able to track this channel. For the case of V2V communication, the channel delay spread is observed to be in between 400ns to 800ns (corresponding to 4 to 8-tap channel) [16]. This implies that a CP of length 7 (L-1 where L is the length of channel) will suffice to counter ISI. Thus, GI has an additional space of 9 samples. In this paper, we utilize this additional space for channel estimation by inserting a pseudo-random sequence in the GI of every OFDM symbol. Since we have a short PRS for channel estimation, we propose decision directed (DD) channel algorithm that is explained below. This decision directed scheme is same as explained in section 3.2.

The first D received time domain samples of $r'_{m,n}$ after A/D conversion denoted in (4.3) can be written as

$$\mathbf{c} = \mathbf{Qh} + \mathbf{e} \tag{4.5}$$

where $\mathbf{c} = [c_0, c_1, \cdots, c_{D-1}]^T$,

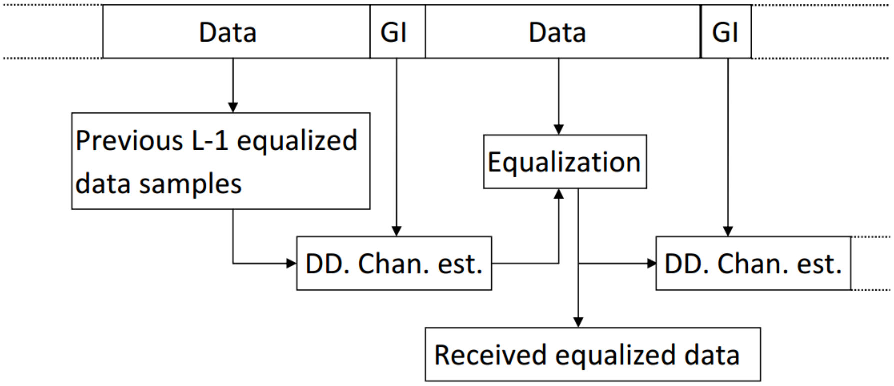


Figure 4.2: Block Diagram of the Proposed Channel Estimation Method

$$\mathbf{Q} = \begin{bmatrix} p_0 & s_{m-1,N-1} & \cdots & s_{m-1,N-L+2} & s_{m-1,N-L+1} \\ p_1 & p_0 & \ddots & \vdots & \vdots \\ p_2 & p_1 & \ddots & p_0 & s_{m-1,N-1} \\ \vdots & \vdots & \ddots & \vdots & p_0 \\ \vdots & \vdots & \ddots & p_{D-L} & \vdots \\ p_{D-1} & p_{D-2} & \cdots & p_{D-(L-1)} & p_{D-L} \end{bmatrix}_{D\times L} \tag{4.6}$$

$s_{m-1,N-1}$ is the $(N-1)^{th}$ sample of the $(m-1)^{th}$ OFDM symbol and $\mathbf{e}$ is the vector of complex baseband additive white Gaussian noise (AWGN) that is assumed to be uncorrelated with the channel. Please note that the first $L-1$ rows of matrix $\mathbf{Q}$ contain the last $L-1$ data samples of the previous OFDM symbol. Since these data samples of the previous OFDM symbol have already been estimated, the use of the estimated symbols in the channel estimate during the current OFDM symbol makes the scheme decision-directed. It is quite obvious that channel estimate will be erroneous in the absence of decision-directed scheme.

With the availability of the PR training sequence and the estimates of $\{\tilde{s}_{m-1,N-1}, \tilde{s}_{m-1,N-2}, \cdots, \tilde{s}_{m-1,N-L+1}\}$ from the previous OFDM symbol, the matrix $\mathbf{Q}$ is estimated as $\tilde{\mathbf{Q}}$ at the receiver end during the GI of the current OFDM symbol. Least squares solution of (4.5) minimizes the risk, R, or the cost function given as below:

$$R = (\mathbf{c} - \mathbf{Q}\mathbf{h})^H(\mathbf{c} - \mathbf{Q}\mathbf{h}) \tag{4.7}$$

Solution of (4.5) under minimum risk R is easily seen to be [14]:

$$\tilde{\mathbf{h}} = \left(\tilde{\mathbf{Q}}^H\tilde{\mathbf{Q}}\right)^{-1}\tilde{\mathbf{Q}}^H\mathbf{c} \tag{4.8}$$

where $\tilde{\mathbf{h}} = [\tilde{h}_0, \tilde{h}_1, \cdots, \tilde{h}_{L-1}]^T$ is the estimated channel in the current OFDM symbol. This proposed solution of channel estimation is labeled as PRwCP decision directed time-domain least squares estimation (PRwCP TDLSE w/DD). The proposed channel tracking scheme is illustrated with block diagram in Fig. 4.2.

4.4 Simulation Results

In this section, we present the simulation results to validate the working of a proposed channel estimation scheme. We simulated data communications via IEEE 802.11p standard for two wireless channel models (as shown in Table-3.1) of DSRC [16]. We used tapped delay line model for generating channel taps with the desired power spectrum profile. We generated each tap after 100ns delay. Maximum channel delay spread is 700ns for the 8-tap channel model and 400ns for the 5-tap channel model, respectively.

In order to assess the uncoded performance of the proposed channel estimation scheme, no error correction codes were used in simulation. In this section, we compare the performance of PRwZP TDLSE and its variants [10, 11] and the proposed PRwCP TDLSE w/DD scheme with reference to bit error rate (BER) versus energy per bit to noise power spectral density (E_b/N_0). Perfect timing synchronisation is assumed at the receiver end. Simulation are carried out via the transmission of 100 OFDM frames over 500 channel realizations and 200 noise realizations. The number of OFDM symbols per frame is 10 and the data is modulated via quadrature phase shift keying (QPSK). Results are generated for slow fading and fast fading scenarios with channel coherence times of 120μs (equal to 15 OFDM symbol duration) and 24μs (equal to 3 OFDM symbol duration), respectively.

Fig.-4.3 & Fig.-4.4 show the simulation results for channel model-1 (8-tap) under both slow and fast fading scenarios where the channel coherence times are 120μs and 24μs, respectively. Similarly, Fig.-4.5 & Fig.-4.6 show the simulation results for channel model-2 (5-tap) under both slow and fast fading scenarios. From these figures, the following observations are in order:

1. The proposed PRwCP TDLSE w/DD scheme works better than the existing schemes that utilize GI for channel estimation in both the slow and fast fading channel scenarios.
2. Number of channel taps affects the performance of the proposed scheme (Fig.4.3 vs. Fig.4.5) and (Fig.4.4 vs. Fig.4.6). For the 5-tap channel model, BER obtained is close to that with perfect channel state information (CSI). Thus, maximum excess delay spread of the channel impacts the performance of the proposed system.
3. Performance of TDLSE scheme remains the same for both (120μs and 24μs), because this scheme estimates channel at the beginning of every OFDM symbol.
4. In the case of fast fading scenario, the existing PRwZP TDLSE with OLA is not able to overcome this problem leading to higher BER (refer to Fig.4.4 and Fig.4.6). Moreover, the performance of OLA based scheme is poor as compared to simple TDLSE (Fig.4.3 vs. 4.4 and Fig. 4.5 vs. 4.6). Thus, OLA based schemes cannot be used for fast fading scenarios.
5. Smoothing based techniques will fail when the channel varies within the smoothing window (as is apparent from Fig.4.4 and 4.6). Also, large smoothing windows may be undesirable in real-time operations because it requires data storage up to the duration of the smoothing window for channel estimation.

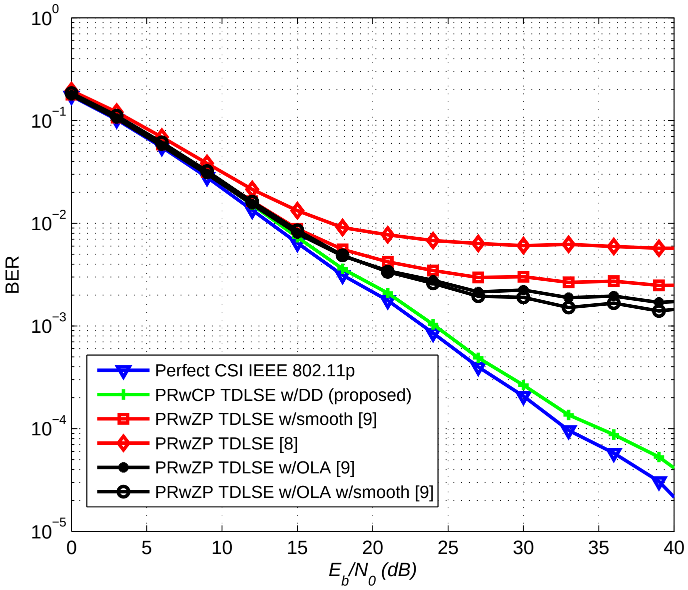


Figure 4.3: BER vs. E_b/N_0, slow fading (coherence time 120μs), 8-tap channel model (Channel-1)

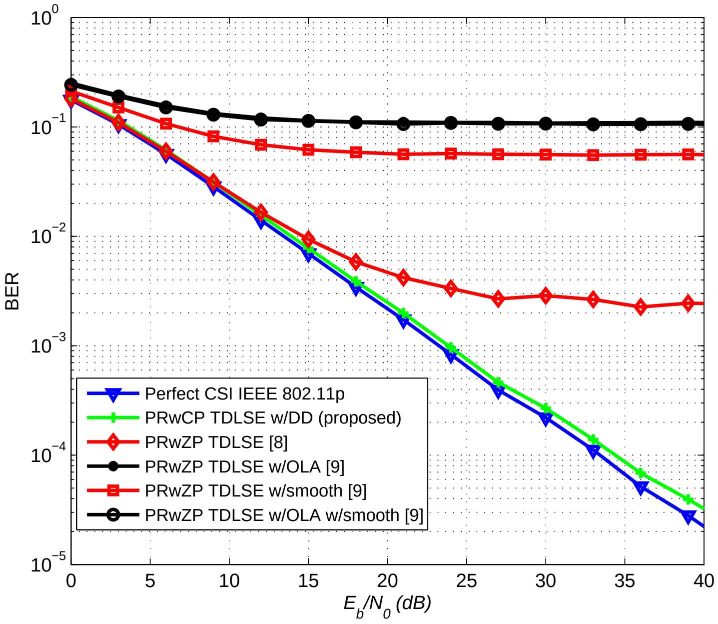


Figure 4.4: BER vs. E_b/N_0, fast fading (coherence time 24μs), 8-tap channel model (Channel-1)

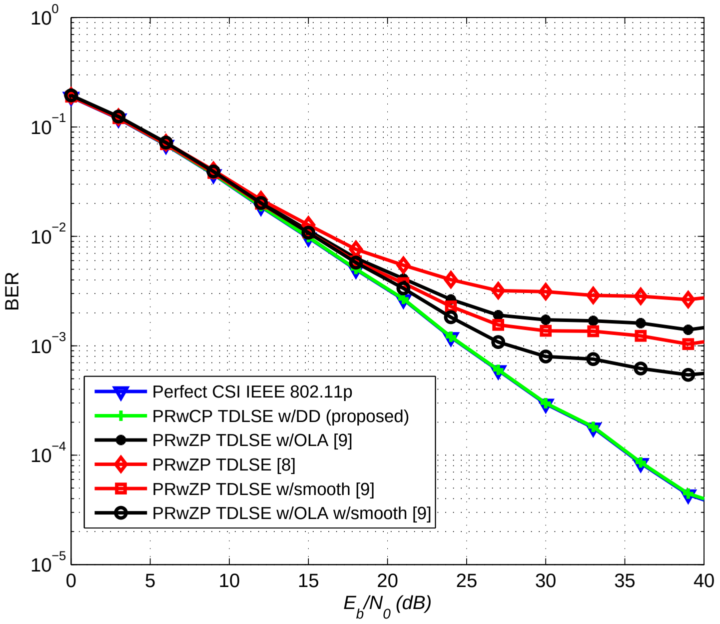


Figure 4.5: BER vs. E_b/N_0, slow fading (coherence time 120μs), 5-tap channel model (Channel-2)

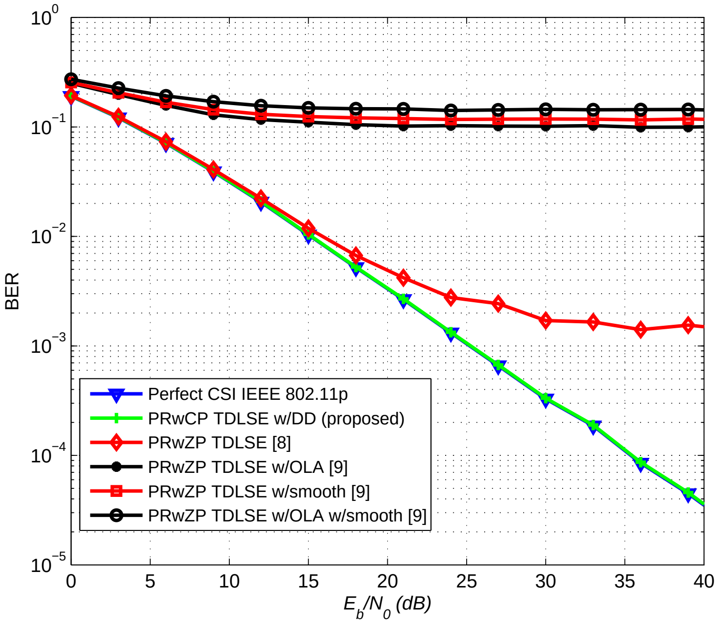


Figure 4.6: BER vs. E_b/N_0, fast fading (coherence time 24μs), 5-tap channel model (Channel-2)

4.5 Conclusions

This chapter presents a novel guard interval based PRwCP TDLSE decision directed channel estimation scheme that is efficient for both slow and fast fading scenarios of IEEE 802.11p wireless standard. The proposed scheme does not restrict the length of CP, but utilizes the redundant space in GI (other than that required for CP) for channel estimation. Thus, the proposed scheme is capable of combating ISI (as CP length is more than channel delay spread) as well as ICI (since it correctly estimates the fast fading channel). Neither there is any reduction of throughput as it does not involve midamble insertion. Moreover, it does not require channel estimation via preamble and hence, effective data rate can be increased via removal of preamble in the future standards. The proposed scheme can address higher wireless data rate challenge for 5G communication besides robust channel estimation for fast fading scenarios.

Chapter 5

Conclusion and Future work

5.1 Conclusion

IEEE 802.11p standard is a dedicated wireless vehicular communication standard meant for outdoor applications. However, for rapidly time varying channel tracking there is no amendment in this standard. Thus, there is a need for reliable channel estimation methods in the receiver end.

In this work we have focussed on the channel estimation in V2V communications. This thesis makes two contributions to the existing research literature. First, a novel time domain decision directed channel estimation method based on RLS is proposed for rapid time varying channel estimation in IEEE 802.11p. The computationally complexity in the proposed method is significantly reduced by recursively updating the channel on an arrival of new sample and with no matrix inversion. Due to the inclusion of decision-directed scheme, the proposed channel estimation method is able to mitigate the effect of ISI and ICI with no overhead of midamble insertion.

Second, a novel guard interval structure based PRwCP channel estimation scheme is proposed. It is efficient for both slow and fast fading scenarios of IEEE 802.11p wireless standard. The proposed scheme does not restrict the length of CP, but utilizes the redundant space in GI (other than that required for CP) for channel estimation. Thus, the proposed scheme is capable of combating ISI (as CP length is more than channel delay spread) as well as ICI (since it correctly estimates the fast fading channel). Moreover, there is no reduction of throughput as it does not involve midamble insertion.

Furthermore, proposed guard interval channel estimation techniques do not require channel estimation via preamble and hence, effective data rate can be increased via removal of preamble in the future standards. The proposed schemes can address higher wireless data rate challenge for 5G communication besides robust channel estimation for fast fading scenarios.

5.2 Future work

Some open issues which can be investigated in future are:

1. In V2V communications, channel may not always change at the beginning of every OFDM symbol. Thus, with the utilisation of pilots, proposed channel estimation scheme can be generalised to any worst case scenario of fast fading.
2. Zero forcing equalizer suffer with noise enhancement problem, hence, it is worth to extend this work using other equalizers.

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