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Virtual Subcarrier-Based Adaptive Channel Estimation Scheme of IEEE 802.11p-Based WAVE Communication System

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Abstract

The IEEE 802.11p-based wireless access in vehicular environments (WAVE) [1] communication is a method used exclusively for wireless communication on the road. This technique enables information sharing not only among moving vehicles but also between vehicles and infrastructure [2]. As part of WAVE communication, data is transmitted to and from vehicles in motion; in this case, it is difficult to determine the channel accurately in an outdoor environment owing to the Doppler shift [3]. This paper proposes a new channel estimation scheme for enhancing the reception performance of the IEEE 802.11p-based WAVE system. The proposed technique obtains the initial channel value by estimating the least square in the time domain by inserting a pilot signal for channel estimation into the IEEE 802.11p virtual subcarrier. Subsequently, a least mean square algorithm is applied to the initial channel value to update the estimated channel value. The simulation results obtained using the proposed channel estimation technique confirm its remarkable efficiency.

Index Terms: Channel estimation, C-ITS, IEEE 802.11p, LMS algorithm, WAVE

I. INTRODUCTION

Next-generation intelligent transport systems have recently emerged to provide diverse communication services in vehicles running at high speeds. These systems are new and environment friendly and offer transport information and services by applying cutting-edge technologies such as the Internet of things to vehicles and transportation facilities. These systems not only make transportation by road easy but also increase safety, convenience, and energy-saving opportunities. A next-generation intelligent transport system requires communication among vehicles, between vehicles and infrastructure, and between vehicles and mobile devices [1-6]. For smooth communication with running vehicles, IEEE 802.11p-based wireless access in vehicular environments (WAVE) was proposed. WAVE is based on WLAN IEEE 802.11a, and it defines the physical layer and medium access control layer for wireless communications [7].

Unlike IEEE 802.11a, IEEE 802.11p WAVE offers improved mobility. Its standard was established in a 10-MHz frequency bandwidth instead of in the 20-MHz band so that optimal performance could be realized in an outdoor environment where frequency interference such as the Doppler shift occurs frequently. Similar to IEEE 802.11a, IEEE 802.11p WAVE estimates channel parameters by using only four subcarriers during one symbol. However, it is difficult to estimate channels by using only four subcarriers in vehicles moving at high speeds in cities or on highways because mobility induces fast changes in channels, and this may cause a serious delay in transmission.

Many studies on various channel estimation techniques that are robust toward time-varying channels have been performed to reduce the delay in the IEEE 802.11p WAVE system [8]. For example, least square (LS), spectral temporal

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averaging (STA), time domain reliable test frequency domain interpolation, and minimum mean square error channel estimation schemes have been proposed [9-18]. However, all of these techniques have performed poorly in time-varying channels [19-24].

Herein, we propose an adaptive channel estimation scheme based on virtual subcarriers. The proposed method obtains the initial channel parameter by applying the LS technique in the time domain and inserting a pilot signal into a virtual subcarrier. Furthermore, the channel parameter of the time-varying channel is estimated by applying a least-mean-square (LMS) algorithm to the estimated initial channel parameter. Our simulation results indicate an outstanding efficiency of the proposed adaptive channel estimation method in terms of the packet error rate (PER).

II. SYSTEM MODEL

The physical layer of IEEE 802.11p operates in the 5-GHz bandwidth based on the orthogonal frequency division multiplexing (OFDM) technique (see Table 1). OFDM refers to a modulation method of multiplexing high-speed transmission signals into multiple orthogonal narrowband carrier waves. Multipath fading can be mitigated by such a method.

Fig. 1 depicts the frame constitution of IEEE 802.11p, where one OFDM symbol comprises 64 subcarriers. Among them, 12 null subcarriers are allocated to positions from –32 to –27, 0, and, from 27 to 32. Four pilot signals are allocated to positions –21, –7, 7, and 21. For the rest of the positions, 48 data subcarriers are allocated accordingly. When the pilot signal is allocated in a comb structure, as shown in Fig. 1, the signal exists in all time domains for one subcarrier. Therefore, it is appropriate for a channel whose signal changes quickly but not for a channel with significant frequency-selective characteristics.

Fig. 2 depicts the block diagrams of IEEE 802.11p WAVE transmitting and receiving systems. IEEE 802.11p is based on the OFDM technique, and one OFDM symbol is com-

Table 1. Parameters in IEEE 802.11p

Preamble duration	32 µs
SIFS duration	32 µs
Guard period	1.6 µs
Signal Field duration	8 µs
Symbol duration	8 µs
Subcarrier	0.15625 MHz
OFDM subcarrier	5
Channel width	10 MHz
Code rate	1/2, 2/3, 3/4
Frequency Band	5.9 GHz
Modulation mode	BPSK, QPSK, 64QAM, 16QAM

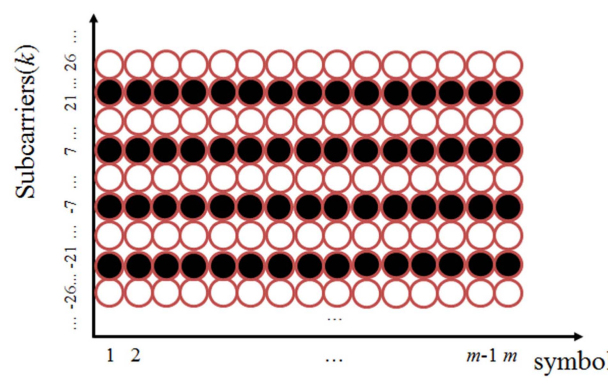

Fig. 1. Structure of 802.11p frame.

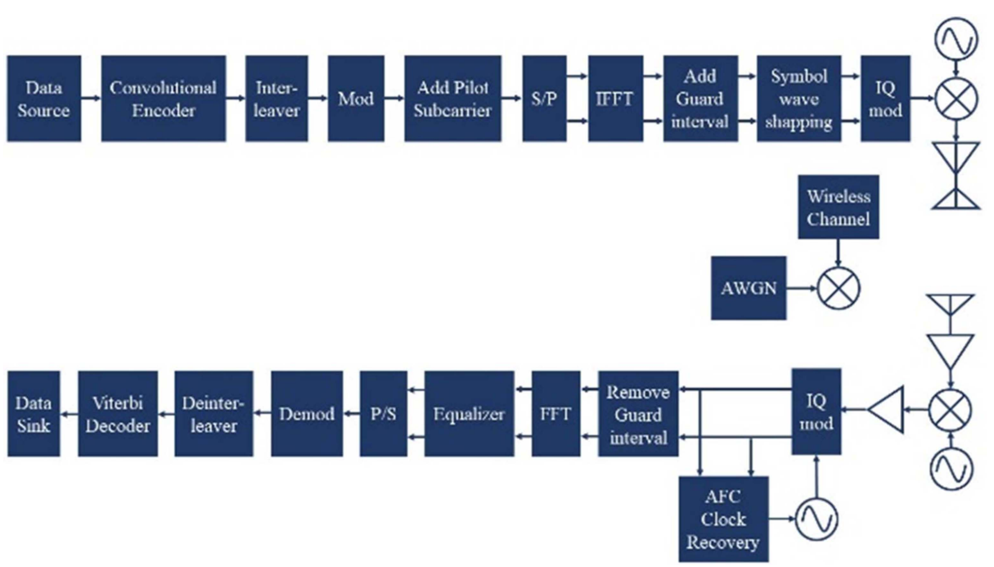

Fig. 2. Constitution of IEEE 802.11p WAVE communication system

posed of 64 subcarriers. Similar to IEEE 802.11a, IEEE 802.11p transmits only four reference signal subcarriers in one symbol period.

III. CHANNEL ESTIMATION TECHNIQUE

Let us now explain the technique of estimating the LS channel in the frequency domain generally used by IEEE 802.11p [25]. This technique estimates the channel by using a pilot signal that the receiver is already familiar with, enabling easy channel estimation with low complexity [26, 27].

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{Z} \tag{1}$$

$$\mathbf{Y} = [Y(0)\ Y(1)\ \cdots\ Y(N-1)]^T$$

$$\mathbf{X} = [X(0)\ X(1)\ \cdots\ X(N-1)]^T$$

$$\mathbf{Z} = [Z(0)\ Z(1)\ \cdots\ Z(N-1)]^T$$

$$\mathbf{H} = \begin{bmatrix} H(0) & 0 & \dots & 0 \\ 0 & H(1) & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & H(N-1) \end{bmatrix}$$

$$\begin{aligned} J(\widehat{\mathbf{H}}) &= \|\mathbf{Y} - \mathbf{H}\mathbf{X}\|^2 = \left(\mathbf{Y} - \widehat{\mathbf{H}}\mathbf{X}\right)^H\left(\mathbf{Y} - \widehat{\mathbf{H}}\mathbf{X}\right) \\ &= \mathbf{Y}^H\mathbf{Y} - \mathbf{Y}^H\widehat{\mathbf{H}}\mathbf{X} - \mathbf{X}^H\widehat{\mathbf{H}}^{\boldsymbol{H}}\mathbf{Y} + \mathbf{X}^H\widehat{\mathbf{H}}^{\boldsymbol{H}}\widehat{\mathbf{H}}\mathbf{X} \end{aligned} \tag{2}$$

where $\mathbf{X}$ is the pilot signal, $\mathbf{Y}$ is the received signal vector, and $\mathbf{H}$ is the actual channel. The gradient of cost function $\mathbf{H}$ is calculated to obtain the value of $\mathbf{H}$ that can minimize Eq. (2) as follows:

$$\frac{\partial J(\mathbf{H})}{\partial(\mathbf{H})} = -(\mathbf{X}^H\mathbf{Y})^* + (\mathbf{X}^H\mathbf{X}\widehat{\mathbf{H}})^* = 0 \tag{3}$$

Vector $\widehat{\mathbf{H}}$, obtained from the LS channel estimation, can be calculated using the following equation:

$$\widehat{\mathbf{H}}_{LS} = \mathbf{X}^{-1}\mathbf{Y} \tag{4}$$

The received signal for each subcarrier in the OFDM system is expressed as the product of the channel and transmitted signal. Therefore, the following equation applies for each subcarrier:

$$\widehat{H}_{LS}(k) = \frac{Y(k)}{X(k)} \tag{5}$$

The LS channel estimation technique enables a simple form of channel estimation. However, it has the disadvantage of the low accuracy of the estimated channel, particularly when noise is present, because the technique amplifies noise in case the channel falls into null. The mean square error (MSE) of the LS channel estimation technique is given by the following equation:

$$\begin{aligned} MSE_{LS} &= E\left[\left(\mathbf{H} - \widehat{\mathbf{H}}_{LS}\right)^H\left(\mathbf{H} - \widehat{\mathbf{H}}_{LS}\right)\right] \\ &= E[(\mathbf{H} - \mathbf{X}^{-1}\mathbf{Y})^H(\mathbf{H} - \mathbf{X}^{-1}\mathbf{Y})] \\ &= [(\mathbf{X}^{-1}\mathbf{Z})^H(\mathbf{X}^{-1}\mathbf{Z})] = \frac{\sigma_x^2}{\sigma_x^2} = \frac{1}{SNR} \end{aligned} \tag{6}$$

The proposed channel estimation scheme is explained in Fig. 3. In the proposed channel estimation technique, a pilot signal is initially inserted into the virtual subcarrier of IEEE 802.11p. Subsequently, pilot signal $d_{pilot}(n)$ defined in advance during the null symbol time is transmitted.

$$x_{pilot}(n) = h(n) * d_{pilot}(n) + z(n) \tag{7}$$

Next, initial parameter vector $\widehat{\boldsymbol{h}}^{(0)}$ is estimated using the time domain LS channel estimation technique, as shown in the following equation:

$$\widehat{\boldsymbol{h}}^{(0)} = (\boldsymbol{d}^H\boldsymbol{d})^{-1}\boldsymbol{d}^H\boldsymbol{x}_{pilot} \tag{8}$$

$$\widehat{\boldsymbol{h}}^{(0)} = [\widehat{h}^{(0)}(0)\ \widehat{h}^{(0)}(1)\ \cdots\ \widehat{h}^{(0)}(L-1)]^T \tag{9}$$

$\widehat{\boldsymbol{h}}^{(0)}$ is the estimated initial channel parameter, and L is the length of channel.

$$\boldsymbol{d} = \begin{bmatrix} d_{pilot}(0) & d_{pilot}(-1) & \dots & d_{pilot}(-L+1) \\ d_{pilot}(1) & d_{pilot}(0) & \dots & d_{pilot}(-L+2) \\ \vdots & \vdots & \ddots & \vdots \\ d_{pilot}(P-1) & d_{pilot}(P) & \dots & d_{pilot}(-L+P) \end{bmatrix} \tag{10}$$

$$\boldsymbol{x}_{pilot} = [x_{pilot}(0)\ x_{pilot}(1) \cdots\ x_{pilot}(P-1)]^T \tag{11}$$

In Eq. (10), d_{pilot} is the pilot signal defined in advance, and P is the number of pilot signals. Channel parameter $\widehat{\boldsymbol{h}}^{(0)}$ estimated in Eq. (8) indicates a low accuracy in a high-noise environment. Therefore, the LMS technique is used based on received pilot $\boldsymbol{x}_p$ to enhance the accuracy of the channel parameter. Channel parameter vector $\widehat{\boldsymbol{h}}^{(i)}$ estimated in the ith iteration by the LMS technique can be stated as follows:

$$\widehat{\boldsymbol{h}}^{(i+1)} = \widehat{\boldsymbol{h}}^{(i)} + \mu\boldsymbol{x}_P(i)e^*(i) \tag{12}$$

where μ is a step-size parameter, and $i = 0, 1, \cdots, N\text{-}1$, with N indicating the length of pilot signals. $e^*(i)$ can be obtained as follows:

$$e(i) = x(i) - \widehat{\boldsymbol{h}}^{(i)H}\boldsymbol{x}_P(i) \tag{13}$$

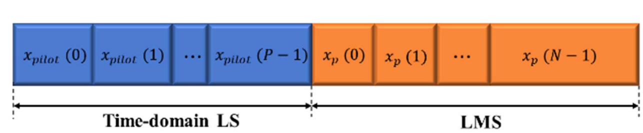

Fig. 3. Adaptive channel estimation schemes based on pilot signals.

$$\boldsymbol{x}_P(i) = [x_p(i)\ x_p(i-1)\ \cdots\ x_p(i-L+1)\ ]^T \quad (14)$$

$$\hat{\boldsymbol{h}}^{(i)} = [\hat{h}^{(i)}(0)\ \hat{h}^{(i)}(1)\ \cdots\ \hat{h}^{(i)}(L-1)]^T \quad (15)$$

Eq. (15) describes the channel parameter estimated in the ith iteration. The final estimated channel parameter is obtained after iterating Eq. (12) N times. The value obtained is a vector in the time domain. Therefore, it is transformed into the channel parameter by converting it into the frequency domain using a fast Fourier transform.

IV. SIMULATION RESULT

The following simulation environment was arranged for the efficiency evaluation of the virtual subcarrier-based new channel estimation scheme in the WAVE system. Tapped delay line (TDL) and power delay profile (PDP) models created with three-dimensional ray tracing were used to consider the spread of delays that occurred in actual urban environments [28]. Table 2 lists the details of the TDL and PDP models used in our study.

To evaluate and analyze the efficiency of the proposed channel estimation technique, an IEEE 802.11p-standard link level simulator was designed and used to compare the performance of the uncoded bit error rate (BER) and PER of the LS technique in the frequency domain with that of the proposed virtual subcarrier-based adaptive channel estimation method. For the channel environment of the simulation, vehicle speeds of 0 km/h and 100 km/h in the urban environment were assumed. For the delayed spread characteristics, the TDL and PDP models described in Table 2 were used.

Table 2. Power delay profile of channel model (urban environment)

Tab number	Delay [ns]	Average power [dB]]	Conversion from Gaussian and CGS EMU to SI a
1	0	0	1 Mx → 10^{-8} Wb = 10^{-8} V·s
2	100	-3.5	
3	200	-5.1	
4	300	-8.0	
5	400	-10.9	
6	500	-14.0	
7	600	-21.5	

Fig. 4 exhibits the MSE performance of the existing and proposed channel estimation schemes in the IEEE 802.11p WAVE system. When MSE is 10^{-2}, the proposed channel estimation technique exhibits an SNR 15 dB greater than that of the existing channel estimation method. This underlines the fact that the experimental and theoretical MSE values are identical. This indicates that the proposed channel estimation method displayed in Fig. 4 performs better than the existing channel estimation method in terms of MSE.

Fig. 5 depicts the result of comparing the uncoded BER of the existing and the proposed channel estimation technique at the 0 km/h speed in an urban environment. In Fig. 5, a zero-forcing (ZF) equalizer is used as the frequency domain equalizer. When the uncoded BER is 2×10^{-3} in the ZF equalizer, the proposed channel estimation technique shows an E_b/N_0 value approximately 3 dB higher than that of the existing channel estimation technique. This result indicates that the new channel estimation technique is better than the existing channel estimation method in terms of the uncoded BER.

Figs. 6 and 7 depict the PER performance comparisons of the existing and proposed channel estimation techniques at speeds of 0 km/h and 100 km/h in an urban environment, respectively. The PER performance in the case of applying a quadrature phase shift keying (QPSK) modulation and channel coding with a 1/2 code rate is analyzed. Fig. 6 depicts that the proposed channel estimation technique can yield an E_b/N_0 value approximately 3 dB higher than that of the LS channel estimation technique when PER is 2×10^{-3}. Upon

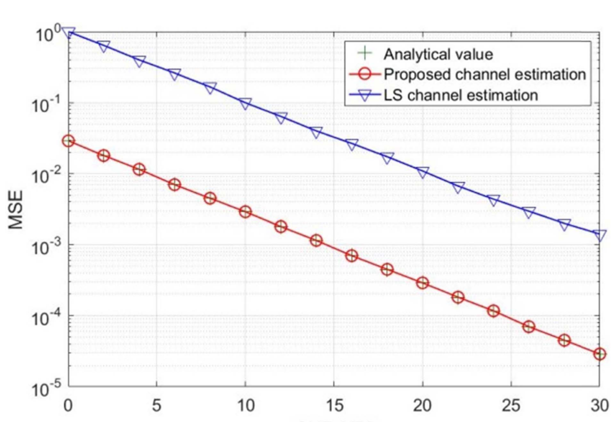

Fig. 4. MSE performance of conventional and proposed channel estimation techniques.

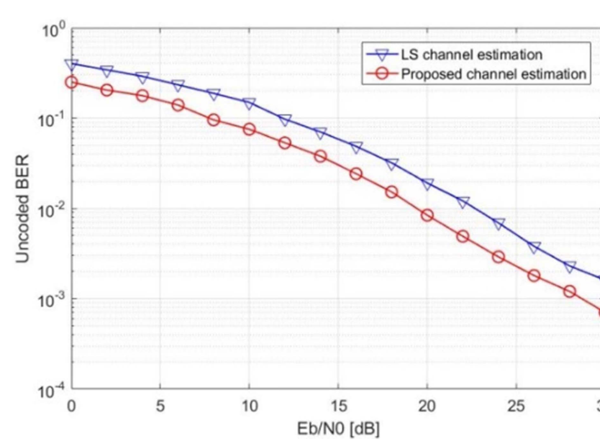

Fig. 5. Uncoded BER performance of conventional and proposed channel estimation techniques.

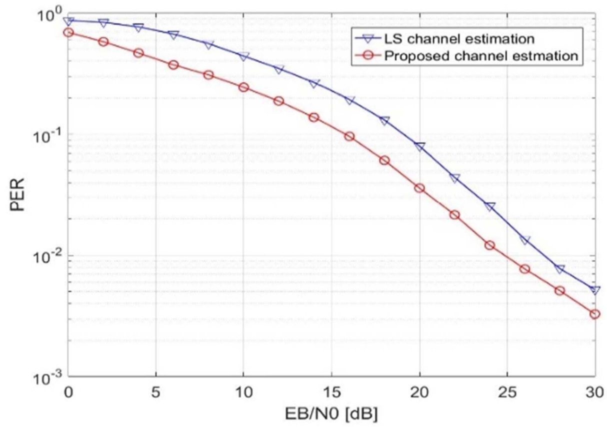

Fig. 6. PER performance in IEEE 802.11p of conventional and proposed channel estimation techniques.

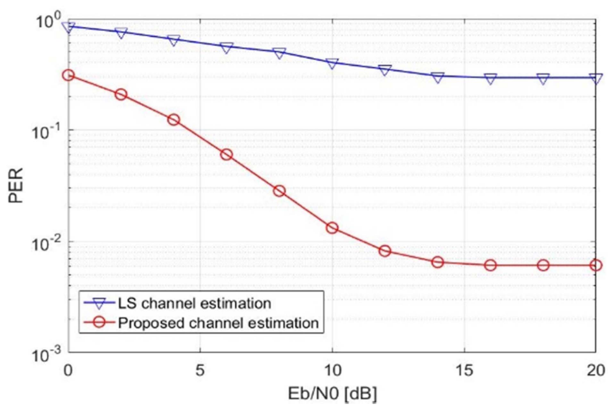

Fig. 7. PER performance at velocity of 100 km/h in IEEE 802.11p for conventional and proposed channel estimation techniques.

comparison of Fig. 6 and Fig. 7, it is observed that the receiver performance of the time-varying channel decreases substantially. However, the increase brought by the proposed technique is maintained. Fig. 7 exhibits that the new channel estimation technique performs better in terms of FER when compared with the existing channel estimation technique.

V. CONCLUSION

This study proposes a virtual subcarrier-based adaptive channel estimation technique for enhancing the receiver performance of an IEEE 802.11p-based WAVE system. The proposed technique may be more complex in terms of the hardware than the existing technique, which estimates the channel by using only the pilot signal because it conducts transmission by inserting the pilot signal in the subcarrier. However, it can substantially mitigate the distortion caused by the time-varying channel. This new channel estimation scheme can significantly enhance the accuracy of channel estimation when compared with the existing channel estimation scheme. Therefore, it can reinforce the reliability of receiving the transmission information in a WAVE system. The new technique proposed in herein is highly applicable for communication among moving vehicles, as well as for the development of self-driving cars, signal-processing fields, and so on.

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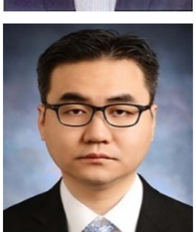

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