Dynamic Channel Estimation over Fast Time-varying Channel for Vehicle Wireless Communications

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Abstract. In vehicle wireless communications, channel characteristics vary rapidly due to the high velocity of the vehicle and rich surrounding scatters. To guarantee a reliable transmission, dynamic channel estimation needs to track the channel changes in the duration of a packet. Within the framework of IEEE802.11p standard, we propose a new channel estimation algorithm that combines data subcarriers and pilot subcarriers to equalize channel response in both frequency domain and time domain. Depending on the changes of the channel, the channel response can be further dynamically equalized by combining the channel response of previous OFDM symbols. Simulations show significant improvement in terms of packet error rate (PER) comparing to the existing methods with little additional computation.

1 Introduction

Wireless Access for Vehicle Environment (WAVE) [1,2] is launched in recent years to realize both vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) telematics services. Reliable and low-latency data transmission plays a key role in fast varying vehicle communication environment. The Orthogonal Frequency Division Multiplexing (OFDM) based IEEE802.11p [3] technique was published in 2010 by extending the IEEE802.11a mechanisms, which was originally designed for indoor scenarios, to the outdoor.

In mobile vehicle environment, the propagation of wireless signal can be shadowed, scattered and diffracted by other vehicles, trees or buildings on the roadside. This condition leads to Doppler shift, short channel coherence time [4,5]. Long delay spread is not a significant problem affecting wireless access by IEEE802.11p based on the previous measurements [4,6], and therefore our attention is focused on other channel impairments. Generally, channel state can not be regarded as a constant over the course of one packet transmission. Therefore, an efficient channel estimator to track the channel variation in such fast varying environment is important.

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A lot of research [7,10,11,8,12,9,13,14] has been done on channel estimation and equalization for OFDM signals, some of which is independent of any given standard. Here, we focus on the channel estimation based on IEEE802.11p system. Conventional channel estimation methods in IEEE802.11p system only adopt two long preambles at the beginning of packet as the guided method in the standard. The performance of channel estimators with only preambles is not guarantied in fast moving environment. In [8], a dynamic channel equalization scheme is proposed, which exploits data subcarriers to aid the channel estimation update. The packet error rate (PER) of data transmissions is significantly improved. However, it does not consider equalizing multiple OFDM symbols in time domain when the channel is fast time-varying. In [9], a modified channel estimation scheme for intelligent packet communication systems adopts additionally the short training OFDM preambles in time domain to improve channel estimation capability, however the scheme only enhances the channel estimation for part of subcarriers position. An iterative reduced-rank channel estimator [10], which is based on generalized discrete prolate spheroidal sequence, obtains the same frame error rate as that with perfect channel state information with additional computational complexity. To reduce the number of implementation iterations, an improved pilot structure is designed by appending OFDM pilot symbol as postamble to the OFDM frame. For OFDM system with carrier frequency offset and phase noise, channel frequency response and phase noise are estimated jointly by employing the maximum *a posteriori* (MAP) criterion in [15].

In this paper, we focus only on receiver-centric improvements, and propose a dynamic channel estimation method based on IEEE802.11p systems over fast time-varying channel by jointly exploiting pilot subcarriers and data subcarriers. Especially, in fast time-varying environment, the relationship between the velocity of vehicle and channel coherence time motivates us to consider that channel frequency response in current OFDM symbol can be further equalized by the channel response of previous correlated OFDM symbols.

The rest of the paper is organized as follows: in section 2, OFDM system model in IEEE802.11p system is described and the problem of channel estimation is stated. Section 3 presents a new channel estimation algorithm for IEEE802.11p system, and the complexity of the presented algorithm is analyzed in Section 4. Section 5 shows simulation results and validates the performance improvement in terms of PER. At last, a conclusion is drawn in Section 6.

2 System Model

The IEEE802.11p standard defines an OFDM-based physical layer to operate in the 5.9 GHz frequency band. An OFDM symbol in frequency domain contains k_d data subcarriers and k_p fixed pilot subcarriers originally designated for frequency offset and phase noise correction, where $k_d = 48$, $k_p = 4$. At the beginning of packet, two long preambles are used to estimate the frequency offset and channel response. The time-frequency structure of the transmitted signal can be described in Fig. 1, where the shadowed tones contain known information.

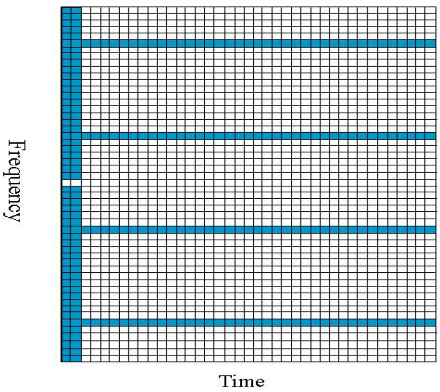

Fig. 1. IEEE802.11p time-frequency frame structure

We consider a packet with N consecutive OFDM symbols, which is transmitted via channel coding, interleaving, modulation and mapping. Denote by $H(i,k)$ the channel frequency response in the ith OFDM data symbol and kth subcarrier, $S(i,k)$ the transmitted frequency signal, $N(i,k)$ the additive white Gaussian noise (AWGN) at the (i,k)th OFDM symbol.

The OFDM signal in time domain can be obtained by performing Inverse Fast Fourrier Transform (IFFT) to the frequency domain symbol:

$$s(i,m) = IFFT\{S(i,k)\} = \sum_{k=0}^{K-1} S(i,k)e^{j2\pi mk/K}, \tag{1}$$

where m is the sampling index in time domain, $K = 64$ is to perform IFFT efficiently. The guard interval is inserted to the output of IFFT operation. The transmitter components and configurations are shown in Fig. 2. In the fast moving scenario, the channel suffers from time varying multipath fading with uncorrelated 2-dimensional isotropic scattering. Denote by $h(i,l)$ the channel impulse response for the lth complex path in the ith OFDM symbol. Channel frequency response $H(i,k)$ can be expressed as,

$$H(i,k) = \sum_{l=0}^{L-1} h(i,l)e^{-j2\pi kl/K}, \tag{2}$$

where $h(i,l) = \sum_{l=0}^{L-1} a_l e^{j\phi_l}\delta(iT_s - t_l)$, L is the number of paths, a_l is complex attenuation coefficient of lth path, ϕ_l is the phase of lth path, and T_s is the duration of an OFDM symbol. The received symbol $R(i,k)$ in frequency domain is

$$R(i,k) = S(i,k) \cdot H(i,k) + N(i,k), \tag{3}$$

where $i = 1, 2, \cdots, N$, and $k = 1, 2, \cdots, K$.

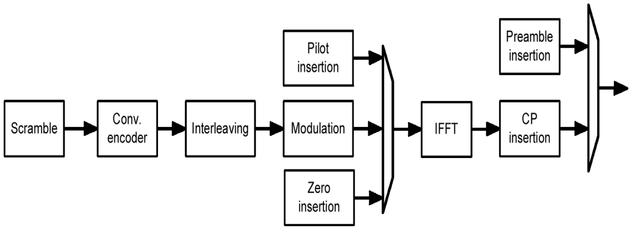

Fig. 2. Transmitter structure of IEEE802.11p physical layer

In the framework of IEEE802.11p standard, the channel can be assumed to be constant over an OFDM symbol, however the channel can change over a packet. In this case, the OFDM symbol duration T_{OFDM} is 8 μs for 10 MHz frequency bandwidth. The central wave length $\lambda = c/f_c$, where $c = 3 \times 10^8$ m/s is the speed of electric and magnetic wave. Assume that the relative velocity of two vehicles is v, and the channel frequency response is essentially invariant over the motion distance of $9\lambda/16\pi$ [16]. The coherence time τ_c over which the time correlation function is above 0.5 is given by

$$\tau_c = \frac{9c}{16\pi v \cdot f_c}. \tag{4}$$

In other words, the number of correlated OFDM symbols is

$$\gamma = \frac{\tau_c}{T_{OFDM}} = \frac{9c}{16\pi v \cdot T_{OFDM} \cdot f_c}. \tag{5}$$

In the vehicle communication case, the relative velocity can be as high as 240 km/h, we know that from eq. (5) the number of correlated OFDM symbols is approximately 16 for 10MHz frequency bandwidth, and the maximum Doppler shift is 1.09 kHz from eq.(6).

$$f_d = \frac{v}{\lambda} = \frac{v \cdot f_c}{c}. \tag{6}$$

When the system operates with the bandwidth 10 MHz, the subcarrier spacing for 64 subcarriers is as high as 156 kHz. The Doppler shift is generally less than 0.6% of the subcarrier spacing. Consequently, the inter-carrier interference is not significant for IEEE802.11p system. The short coherence time, on the other hand, can be a primary source of performance degradation, and this leads to the need of dynamic channel estimation. In the next section, we propose a new algorithm to dynamically update the channel response over the course of one packet to combat for the short coherence time.

3 Channel Estimation

For simplicity, we omit the noise item in this section. It is straightforward to estimate the channel response using known transmitted data, i.e. the short and long training OFDM symbols and pilot subcarriers by the least-square channel estimate

$$\hat{H}(i,k) = \frac{R(i,k)}{S(i,k)}. \tag{7}$$

For conventional channel estimation algorithms, the above channel estimation result is used for equalization throughout the packet. Furthermore, the channel estimation of subsequent OFDM symbol is updated by the pilot subcarriers using interpolation method.

When channel is not fast varying, the initial channel estimation obtained by preambles can be adopted to the following symbols. When the vehicle moves fast, channel correlations between OFDM symbols become small. The initial channel estimation can be outdated after the first few symbols. On the other hand, when the packet undergos multipath fading and delay spread, the pilots are not spaced closely enough to sample the channel variations in the frequency domain. The performance of conventional channel estimation algorithms is not satisfactory. Consequently, in V2V and V2I scenarios, an effective channel estimator must dynamically track the channel variation in both frequency and time domain.

To combat the fact that there are not enough pilot subcarriers, data subcarriers can be used to aid channel estimation. The noise in each subcarrier can be regarded as independent, the channel estimation accuracy can be improved by utilizing the correlation of channel response in subchannels. For example, in [8], several data subcarriers are exploited to make a single measurement at the given kth subcarrier.

With the received signal at the kth subcarrier and the ith data symbol $R(i,k)$, the transmitted signal can be recovered using the channel estimation of the $(i-1)$th symbol:

$$\hat{S}(i,k) = \frac{R(i,k)}{H(i-1,k)}. \tag{8}$$

When a decision of the received data is made, the channel estimation of ith symbol at kth subcarrier is updated by

$$H(i,k) = \frac{R(i,k)}{X(i,k)}, \tag{9}$$

where $X(i,k)$ is the estimated data after decision.

Since the estimation result (9) is suffering from measurement noise, combining adjacent subcarriers into the given subcarrier can help to reduce the effect of a single channel measurement noise. The linear combination of channel estimation in frequency domain for a given (i,k) OFDM symbol is expressed as

$$H_F(i,k) = \sum_{\iota=-\alpha}^{\alpha} w_\iota H(i,k+\iota), \tag{10}$$

where α is the number of adjacent subcarriers on one side for average, and w_ι is the weight of each subcarrier, and $\sum_{\iota=-\alpha}^{\alpha} w_\iota = 1$. The weight of subcarriers closer to the pilot subcarriers can be assigned a bigger value, because the channel estimation for these subcarriers has better performance.

To average the channel estimation, the channel needs to be extended for the first and last subcarrier, and the whole channel response is constructed for the ith symbol as $[H(i,\alpha+1),\cdots,H(i,2),H(i,1),\cdots,H(i,K),H(i,K-1),\cdots,H(i,K-\alpha)]$. Since the zero subcarrier is not used to data transmission, so the value of $H(i,27)$ is replaced by $(H(i,26)+H(i,28))/2$.

Considering the fast variation of channel state, we should iteratively update the channel estimation depending on the changes of the channel. The combination of several channel estimation algorithms in the coherence time makes the channel estimation of current symbol more reliable.

$$H_T(i,k)=\sum_{\kappa=1}^{\gamma}\frac{p^{\gamma-\kappa}}{\sum_{\kappa=1}^{\gamma}p^{\kappa}}H(i-\kappa,k), \tag{11}$$

where γ can be chosen according to eq. (5) and is related to the velocity of vehicle, and p is the weight factor for each OFDM symbol in the coherence time (a large p implies more weight for the previous OFDM symbols which are closer to the current OFDM symbol). Note that γ maybe a rough estimaiton in the case with high velocity. The more precise threshold for the coherence time can be defined, and the number of correlated OFDM symbols can be chosen. Therefore, eq. (11) shows that the channel estimation update rate can be adjusted according to the change of the channel. It facilitates to dynamically track channel state and is expected to improve the performance. When the channel estimation is averaged in frequency and time domain respectively, we consider the final channel estimation as follows,

$$H(i,k)=(1-\frac{1}{\beta})H_T+\frac{1}{\beta}H_F. \tag{12}$$

where β is determined by getting a balance between time dimension and frequency dimension.

To start the iterative procedure, the initial channel estimation $H(0,k)$ is calculated from the preamble symbols. The channel response of subsequent OFDM symbols are obtained from (12). The procedure is repeated until all OFDM symbols are processed.

4 Complexity Analysis

The proposed iterative channel estimation algorithm is complied to operate in IEEE802.11p system. The complexity of the presented method is determined by two steps:

1. Initial estimation
   This process includes the estimation of channel response by the direct decision of the received data. By eq.(8) and (9), the initial estimation involves $2NK$ complex divisions for all OFDM symbols in each subcarriers.

2. Iterative estimation
   The channel estimation in frequency dimension combines the adjacent subcarriers. The execution includes $(2\alpha + 1)$ multiplications and $(2\alpha + 1)$ additions, where α has generally small value.
   The dominant factor in the computational complexity is iterative channel estimation in time dimension. From eq.(11), the algorithm involves γ^2 multiplications and $2(\gamma - 1)$ additions to obtain the estimation of each OFDM symbol.

In total, the complexity of the presented algorithm in term of floating point operations is $(\gamma^2 + 2\gamma + 4\alpha + 7)NK$. Comparing to other iterative channel estimation algorithms, e.g., see [10], our channel estimation method achieves good channel response without increasing the computational load.

5 Simulation Results

In this section, we study the performance of the proposed channel estimation method. In the simulation, we consider an uncoded input that is modulated by the QPSK modulation. Without loss of generality, the results can be easily extended to other modulations. The PER is determined based on the transmission of 10^6 packets, and the parameters α, β, p in (10), (12) and (11) are chosen to be 2, 2, and 3, respectively. In each simulation, we only model narrowband fading, where all multipath components are received within a single symbol period. The channel model is given by $h(i, l)$ in eq.(2). Fig. 3 is an example of channel response variation of the normalized fading power envelope. The signal is transmitted at a bandwidth of 10 MHz with central frequency band of 5.9 GHz.

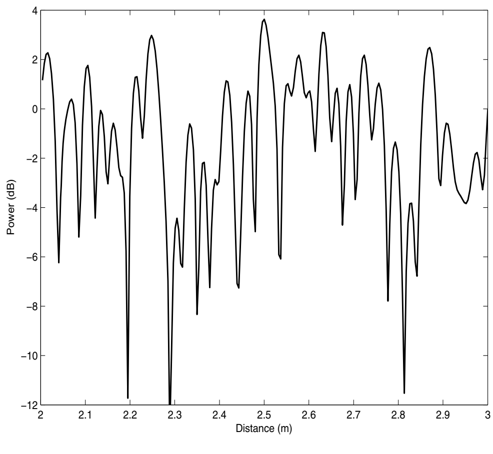

Fig. 3. Example of channel response variation of the normalized fading power envelope, where the vehicles travel relatively at 100 km/h

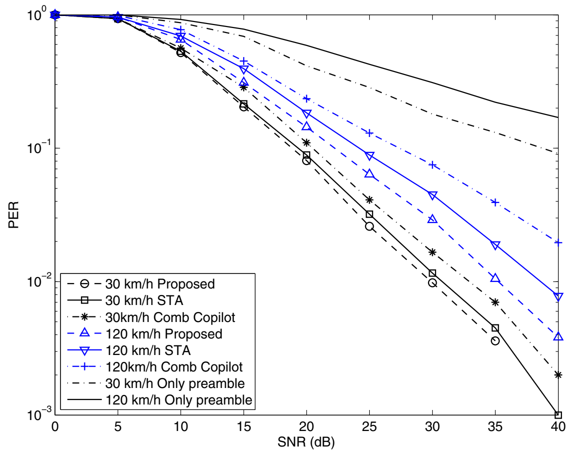

Fig. 4. PER comparison of the proposed algorithm, STA algorithm and Comb Copilot algorithm for velocities $30, 120$ km/h, corresponding to maximum Doppler shift $164, 656$Hz with fixed packet length 100 symbols

In the first simulation, PERs are shown in the cases with different velocities for STA (Spectral Temporal Average) channel estimation method [8], comb copilot interpolation (Comb Copilot) method [12], only preamble method, and our proposed method. In the simulation, we fix packet length to 100 OFDM data symbols, and choose two velocities 30 and 120 km/h, corresponding to Doppler shift values of $f_d = 164, 656$ Hz, respectively. Fig. 4 shows that the performance degrades for all algorithms with the increase of velocity. However, our algorithm always obtains lower PER than other algorithms. In comb copilot scheme, several data subcarriers are used as pilots to perform a linear combination in different data subcarriers. From eq. (5), we know that the channel responses of the less number of correlation OFDM symbols are averaged when the vehicle moves at a larger velocity. Therefore, when a single channel response is obtained with measurement error, it will lead to a smaller probability that the channel response is correctly estimated by averaging multiple measurements, and further affects the equalization to recover the transmitted data.

Next, we analyze the system performance for the proposed channel estimation algorithm with different packet length. From Fig. 5, we find that increasing the packet length degrades the PER performance for all algorithms. That is because the short coherence time in fast varying environment, the channel estimation by the known preambles is quickly outdated. However, our algorithm keeps a significant improvement $(2 - 10\text{dB})$ for all packet length values compared to STA algorithm and Comb Copilot algorithm.

In the last experiment, since the channel coherence time is related to the velocity of the vehicle, it is interesting to evaluate PER performance of three algorithms in terms of the velocity. In the simulation, packet length is fixed to 120 and the value of SNR is set to 30 dB. From Fig. 6, we see that PER

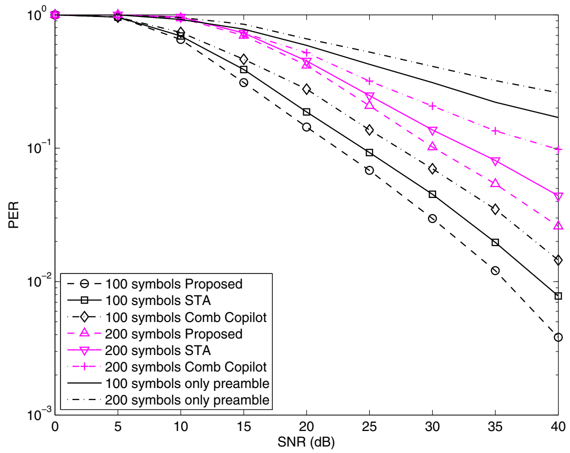

Fig. 5. PER comparison of the proposed algorithm, STA algorithm and Comb Copilot algorithm for different packet length in the case where the vehicles travel relatively at the fixed velocity of 120 km/h

is improved by our proposed algorithm in the cases with different velocities comparing to STA algorithm and Comb Copilot algorithm.

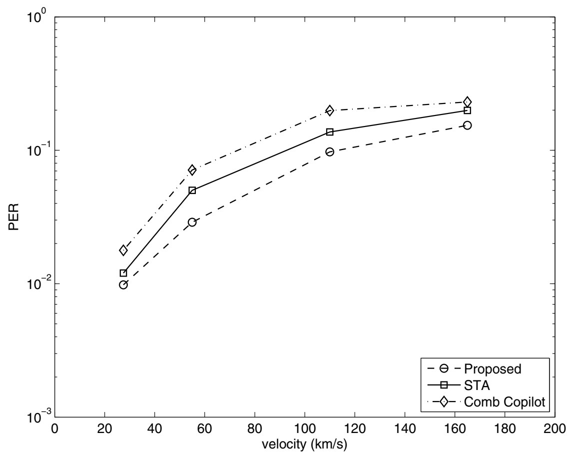

Fig. 6. PER comparison of the proposed algorithm, STA algorithm and Comb Copilot algorithm in terms of velocity for fixed packet length 120 symbols and SNR=30 dB

6 Conclusion

In vehicle wireless communications, the rich scatters and high mobility make the channel vary fast over the course of one packet transmission. The change of channel leads to the need of a channel estimator that can track the channel variation in such environment. In this paper, we first analyze the relationship between channel coherence time and vehicle velocity, which further determines the length of averaged channel response in time domain during the channel estimation. To reduce the effect of the noise in the channel estimation, we combine the data subcarriers and pilot subcarriers and average the channel response in frequency domain. In addition, channel response in subsequent OFDM symbols is iteratively equalized. Simulation results obtained in different scenarios prove the effectiveness of the proposed method.

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