A Robust OFDM Receiver for DSRC Systems

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Abstract: - OFDM PHY has been selected as North American DSRC standard (IEEE 802.11p). In this paper, we present a robust OFDM receiver suitable for DSRC systems. A synchronizer, a one-tap frequency domain equalizer (FDE), a pilot-based phase estimator and a Viterbi decoder mainly compose it. The equalizer uses normalized least-mean-square (NLMS) algorithm to track not only the variation of the DSRC channel in 5.9GHz band but also the residual frequency/phase errors that are not yet being entirely corrected by the synchronizer device. In order to keep the NLMS equalizer working well, we utilize a pilot-based phase estimator to help estimate them. For getting more improvement, a code decision directed demodulation (CD3) scheme assisted by the decoder outputs could be adopted to help track. The simulation results indicate that our proposed OFDM receiver works fairly well for two DSRC channel models.

Key-Words: - OFDM, DSRC, FDE, NLMS, CD3

1 Introduction

As an important part of the ITS (Intelligent Transportation System), DSRC (Dedicated Short Range Communication) can provide many advanced services such as ETC (Electrical Toll Collection), parking management, traffic flow monitoring, emergency vehicle signal preemption, intersection collision warning, and so on. Recently, the well-known IEEE 802.11 organization has formed a task group (TGp) aimed at finishing a DSRC standard, IEEE 802.11p. They have chosen OFDM (Orthogonal Frequency Division Multiplexing) techniques as the PHY part that is very similar to that of 802.11a. For example, they have the same frame structure, the same definition of the preambles, the same encoder/decoder, etc. The major difference is due to the channel bandwidth, 10MHz for DSRC and 20MHz for 802.11a. It makes them different in symbol duration, carrier spacing and data rate.

The DSRC mainly concerns with two scenarios [1], one is the communication between an moving OBU (On Board Unit) and an fixed RSU (Road Side Unit), the other is the communication between an moving OBU and another moving OBU. Therefore, two DSRC channel models must be well defined for the two scenarios. Analysis and experiment must be also taken care for the suitability of the OFDM-based PHY. Several researches [12], [13] have targeted for the first scenario and assured the feasibility of OFDM. However, few researches have targeted for the second one for lack of the channel model. In recent 802.11p progress, the vehicle-vehicle channel model [1] has been defined from plenty experimental data. That motivates us to evaluate the performance of our OFDM receiver [2] for the two DSRC channel models.

The organization of this paper is as follows. Two DSRC channel models are introduced in section 2. The impairments on an OFDM receiver including the channel effect, sampling frequency offset (SFO), carrier frequency offset (CFO) and residual CFO are described in section 3. The main structure of our proposed receiver including a synchronizer, an FDE, a pilot-based phase estimator and a Viterbi decoder is described in section 4. Some well-known OFDM receivers are also introduced in this section. The simulation and conclusion are made in section 5.

2 Two DSRC Channel Models

The first channel model for the communication between an OBU and an RSU is a two-path (one-tap) model [12], [13], which includes a direct path with a Doppler shift and a non-direct Rayleigh path with a classic Jake’s Doppler spectrum due to the moving velocity.

The second channel model for the communication between an OBU and another OBU in the same direction is a 12-path (10-tap) model [1], as shown by Table 1.
In which the first three paths compose the first tap and each path is with its own Doppler spectrum. In the following, we list the functions for variable spectrums. The classic 6 (Jake’s) is with

\[ S_k(f) = \begin{cases} a \left[ 1 - \left( \frac{f - fd}{ff} \right)^2 \right] & \text{if } |f - fd| < 0.999ff \\ 0 & \text{otherwise} \end{cases} \]

The rounded one is with

\[ S_{rounded}(f) = \begin{cases} a \left[ 1 - \left( \frac{f - fd}{ff} \right)^2 \right] & \text{if } |f - fd| < 0.999ff \\ 0 & \text{otherwise} \end{cases} \]

The flat one is with

\[ S_{flat}(f) = \begin{cases} a & \text{if } |f - fd| \leq ff \\ 0 & \text{otherwise} \end{cases} \]

where \( ff \) is the maximum Doppler shift (for the path) and \( fd \) is the Doppler offset (the point of symmetry of the spectrum shape). The truncation of the region of support for this spectrum to 0.999ff avoids the singularities and achieves approximately 6 dB from the peaks to the trough of this spectrum shape. The factor \( a \) is chosen so that the integral of the spectrum (the average power of the path) is set to a specified value, for examples, as listed in Table 1.

<table>
<thead>
<tr>
<th>Path No.</th>
<th>Tap No.</th>
<th>Tap Power (dB)</th>
<th>Path Power (dB)</th>
<th>Exposure Delay (ns)</th>
<th>Doppler Offset (Hz)</th>
<th>Doppler Spectrum Half Width (Hz)</th>
<th>Angle of Arrival (deg)</th>
<th>Spectrum shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>-20.397</td>
<td>0</td>
<td>0</td>
<td>-37.8</td>
<td>0</td>
<td>Flat</td>
<td>Round</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>-15.297</td>
<td>0</td>
<td>0</td>
<td>-38.7</td>
<td>0</td>
<td>Rounded</td>
<td>Round</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>-15.7</td>
<td>0</td>
<td>0</td>
<td>-38.8</td>
<td>0</td>
<td>Flat</td>
<td>Round</td>
</tr>
</tbody>
</table>

3 The Impairments on An OFDM System

The basic block diagram of an OFDM system is illustrated in Fig. 1. We consider an OFDM system with N subcarriers. The baseband OFDM signal in the transmitter can be expressed as

\[ x_{k,l} = \frac{1}{N} \sum_{n=0}^{N-1} X_{k,l} e^{j2\pi kn/N} \]
Equation (6) can be separated into two parts, one part is dependent of l and the other is not. Therefore we have

\[ Y_{k,l} = X_{k,l}H_{k,l}e^{-j2\pi f_{l}(l)} \cdot g_k + I_{k,l} + N_{k,l} \]  

(7)

Where \( f_{l}(l) = (k + \Delta k)(1 + \Delta e)N_j/N \) and

\[ g_k = \frac{1}{N} \sum_{n=0}^{N-1} e^{-j2\pi [\Delta k + (1 + \Delta e)k]n/N} \cdot e^{-j2\pi (k + \Delta k)\theta/N + \theta_0}. \]

The magnitude of the first summation term of \( g_k \) is approximate to 1 when \( \Delta k \) and \( \Delta e \) are small. Equation (7) indicates that the OFDM receiver should enter into the tracking stage to compensate \( H_{k,l}, f_{l}(l), \) and \( g_k. \) The remaining magnitude/phase errors can be compensated by an adaptive FDE. However, if the SFO or the residual CFO is still large, then the FDE may not have good convergence behavior. To avoid such a situation in our proposed structure, we have utilized a pilot-base estimator and/or a CD3 scheme to help it. More details are described in section 4.

4 The Proposed OFDM Receiver

The 802.11p frame structure composed by preambles and data is show in Fig.2. The preambles consists of ten identical short OFDM symbols and two identical long OFDM symbols. They preceding the useful data are required to help successful synchronization and detection of the data. Similar frame structures in many reliable communication systems are usual because the known patterns of preambles can provide much useful information. In addition to the preambles, four pilots to help tracking are inserted among the used 52 subcarriers in each data symbol. However, the preambles and pilots which act as redundancy also somewhat degrade the system throughput.

![Fig.2, IEEE 802.11p frame structure.](image)

In this section, we compare two well-known receiver structures \((A, B)\) with our main structure \((C)\). For getting more improvement, a CD3 scheme applied for the structure \((C)\) leads to the structure \((D)\). We briefly describe them as follows.

4.1 Pilot-assisted Non-adaptive FDE

This receiver structure mainly utilizes the long preambles to obtain the channel estimation, \( \hat{H}_{k,0} \). The channel effect is compensated for all the following data symbols by a non-adaptive one-tap FDE with the estimated value at each subcarrier. Besides, four pilots in each data symbol are responsible for compensating the residual CFO and SFO [11]. This structure is suitable for time-invariant channels such as the IEEE 802.11a channel model.

4.2 CD3-assisted adaptive FDE

This receiver structure takes the initial estimated \( \hat{H}_{k,0} \) from the long preambles to compensate the first received data symbol. Then, the Viterbi decoder decodes the data symbol and the decoded data is feedback to the channel estimator. Because the decoded data are much more reliable, they can be used to update the estimated \( \hat{H}_{k,l}, \) for \( l > 0 \). The estimation also actually reflects the effects of the residual CFO and SFO. The basic idea of a CD3 scheme is depicted in Fig.3. The update process is through a time-domain filter and a frequency-domain filter. According to [3], the time-domain filter simply averages all coming inputs. The behavior of the filters is quite influential to the system performance for different time varying channels.

![Fig.3, the basic concept of CD3](image)

4.3 Adaptive FDE with NLMS

Our proposed OFDM receiver structure mainly including frame detection, frequency estimation, timing synchronization, and an adaptive FDE with help of a pilot-based phase estimator are illustrated in Fig.4.
The short preambles can help the input signal achieve synchronization in the acquisition stage as the three blocks indicated. They are frame detection block, coarse CFO estimation block and coarse symbol timing block. Usually, a correlator utilizing the periodic characteristic of these short symbols can be employed to detect the presence of a frame, to coarsely estimate CFO and symbol timing. Many algorithms [6]-[8] have been discussed for these processes. We do not discuss these synchronization algorithms for concise in this paper. The designed structure and the signal flow are the main part. One can always refer these algorithms of synchronization to our designed structure to obtain satisfactory results.

Fig. 4, the proposed OFDM receiver structure.

After passing through the FFT device, the processed OFDM symbols enter into the second stage that is indicated in the lower half of Fig.4. Similar to other OFDM systems [4]-[5], a one-tap FDE at each subcarrier is used for compensation. It compensates both the magnitude and phase distortion caused by the channel. We make the FDE be adaptive in our design, as shown in the update coefficients block, such that it can not only compensate the channel impairment but also do the other impairments. The initial values of the FDE coefficients, as shown in the initial block, are obtained from the long preambles [9]. The initial values are mainly used to compensate the channel effects. From (7), if the ICI term and AWGN noise are negligibly small, then the value of the FDE coefficient, \( w_{k,l} \), at the k-th subcarrier is with

\[
 w_{k,l} = \frac{1}{H_{k,l}} e^{j2\pi f_{k}(l)} .
\]

We may note that the magnitude/phase error does increase with \( l \) if SFO or residual CFO or both of them exist. That is the reason why the FDE ought to be adaptive. Although a mechanic feedback control [10] can be used to actually adjust the sampling frequency and oscillator frequency for compensating SFO and CFO, some digital signal processing (DSP) algorithms [11] are simpler to do that in mathematical equivalence as what we shall do here.

In the designed structure, we select NLMS algorithm for the adaptive FDE to track the error at each subcarrier. The value of residual CFO influences the convergence behavior of the FDE. Once the residual CFO is too large, the NLMS equalizer cannot closely approach the error and may eventually lead to divergence. In order to reduce the probability of divergence, we present a pilot-based phase estimator to help estimate the phase error. The estimated phase error is then feedback to update the FDE coefficients. By doing so, the NLMS equalizer works more robust than other known non-adaptive ones or even adaptive ones.

The NLMS algorithm is described as follows. Let \( w_{k,l} \) be the coefficient of the FDE at the k-th subcarrier in the l-th OFDM symbol. The initial value (when \( l=0 \)) of it is calculated by the long preambles. The update equation by using the NLMS algorithm can be written as

\[
 w_{k,l+1} = w_{k,l} + \mu_{k} \frac{e^{*}_{k,l} Y_{k,l}}{\| Y_{k,l} \|^{2}}
\]

where \( \mu_{k} \) is the step size, \( e^{*}_{k,l} = d_{k,l} - w_{k,l}^{*} Y_{k,l} \) is the error between the desired value and equalized value and \( \langle \cdot \rangle \) represents a time-average function. The step size at each subcarrier should be carefully chosen to prevent the NLMS equalizer from being diverged. One can refer to [2] about the determination of the suitable step size.

Another advantage in our structure is that the FDE can either compensate only the phase error or does both of the magnitude and phase error at each subcarrier in the meanwhile, as the usual FDE do. In the former case, we postpone the compensation of the magnitude error at the Viterbi decoder. The estimated magnitude information can serve as the channel state information to help better decoding performance. In general OFDM systems, pilots are usually needed for tracking any variation of environment, especially...
the variation of the channel. Different placement of pilots is required for different systems due to different application environment. Preambles and data compose the 802.11p frame structure. In the data section, four pilots in each OFDM symbol are placed at −21, −7, 7, 21-th subcarriers to help the tracking process. The pilots mainly function on the impairments including the time varying effect of the channel, the residual CFO and SFO. As the aforementioned, the phase error at each subcarrier results from the residual CFO and SFO can not be ignored because it increases with l. The proposed receiver does not mechanically adjust sampling frequency to overcome the SFO impairment. Instead, the SFO is mathematically eliminated by using a pair of pilots at opposite subcarriers, such as −7, 7 or −21, 21 [11]. The residual CFO can also be accurately compensated then. However, this method takes some risk for the sake that only two pairs of pilots are available. Once the channel happens to be fade on some of these pilots, the estimation is easily incorrect.

To avoid such a risk, we give the pilot-based estimator a special task, which is somewhat different to the aforementioned [11]. The task of it is to calculate the total phase variation caused by all impairments including the channel effect, SFO and residual CFO in each OFDM symbol and feedback the estimation of it to the adaptive FDE. The adaptive FDE employing NLMS algorithm can therefore track the magnitude/phase error at each subcarrier in successive OFDM symbols. Note that we do not use pairs of pilots for the purpose of canceling SFO. The operations make our system more robust in resistance with the impairments. By using the adaptive FDE, our designed structure will also be more resistant for the time-varying channel. The method of estimation for the pilot-based estimator can be either EGC (equal gain combining) or MRC (maximum ratio combining). We choose MRC for it gives better performance. The reason is that, for a frequency selective channel, the better subchannel offers more reliability. The goodness of a subchannel is determined from the preambles. The MRC method is very effective even though only one pilot is still reliable.

As we have previously mentioned, the FDE block in Fig.4 can either compensate only the phase error or do both of the magnitude and phase error at each subcarrier in the meanwhile. Note that, the rule of the hard decision block is different in the two cases. In the former case, changing the scale of the original signal constellation by the factor of |1/w(k,0)| is required. The estimated magnitude information, |1/w(k,0)|, should be notified to the Viterbi decoder to help decoding. The following simulation shows that our proposed structure with the help of a pilot-based estimator and an adaptive FDE can efficiently overcome the impairments. It also shows that the NLMS algorithm for the adaptive FDE converges well.

4.4 CD3-assisted Adaptive FDE with NLMS
This enhanced structure could be regarded as the combination of structure (C) and structure (B). The decoder output that replaces the output of the hard decision is sent back to the coefficient-update block. Because the decoder output is more reliable, this structure could be more robust than structure (C).

5 Simulation and Conclusion
The preambles include ten short and two long symbols which are used for frame detection, AGC (auto gain control), CFO estimation, symbol timing detection and channel estimation. In the simulation, the AGC that normalizes the average power of the received signal is considered to be ideal. The coarse CFO estimation and symbol timing is achieved by the last three short symbols as suggested by the 802.11p standard. The estimated CFO is compensated for the following long symbols and data symbols through a NCO. No fine CFO estimation is needed by the two long preambles for the sake that the coarse estimation is satisfactory. However, the channel estimation is made by the two long symbols to obtain the initial coefficients of equalizer, \( w^{*}_{k,0} \). The parameters are set as follows. Data payload is 512 bytes, i.e. 86 data symbols for BPSK modulations. CFO is 1.5 times carrier spacing, i.e. 234.375kHz. SFO is 40 ppm. As we have expected. From Fig.5 and Fig.6, the Rician channel seems to be more destructive than the 12-path channel. For 16QAM modulations, the simulation results not shown in this paper are similar. Both figures indicate that the proposed structure (C) significantly outperform the structure (A) and (B) and is slightly worse than the proposed structure (D). We can conclude that when the channel is time varying...
due to the vehicle velocity, our proposed receiver with adaptive NLMS FDE can overcome the impairments and performs even better with assistance by a CD3 scheme.

In this paper, we have proposed a robust OFDM receiver for DSRC systems. The core of it includes a synchronizer, a one-tap FDE and a pilot-based phase estimator as shown in Fig.4. The equalizer uses NLMS algorithm to track not only the variation of the channel but also the magnitude/phase errors that are not being previously corrected by the synchronizer device. In order to keep the NLMS equalizer working well, we utilize a pilot-based phase estimator to help estimation the channel variation and the phase error. The designed receiver combining a CD3 scheme performs better. The simulation results prove our design very suitable for DSRC communications.

Fig.5, BPSK modulations for the Rician DSRC channel.

Fig.7, BPSK modulations for the 12-path DSRC channel.

References: