Channel Estimation and Tracking Algorithms for Harsh Vehicle to Vehicle Environments

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***Abstract*—The vehicle-to-vehicle (V2V) communication channels are highly time-varying, making reliable communication difficult. This problem is particularly challenging because the standard for V2V communication (IEEE 802.11p standard) is based on the WLAN IEEE 802.11a standard, which was designed for indoor and relatively stationary channels.**

In this paper, novel channel estimation and tracking algorithms for highly time varying channels are proposed. The proposed algorithms utilize the finite alphabet property of the transmitted symbol, time domain truncation, decision-directed feedback, pilot information as well as V2V channel characteristics. The proposed algorithms improve the overall system performance in terms of bit error rate, enabling the system to achieve higher data rates and larger packet lengths at high relative velocities. Simulation results show that the proposed algorithms achieve improved performance for all the V2V channel models with different velocities, and for different modulation schemes and packet sizes as compared to the conventional least squares estimator and other previously proposed channel estimation techniques for V2V channels.

I. Introduction and Related Work

To realize many future applications in the vehicular communication that vary from simple safety messages and infotainment to autonomous driving, a robust network of connected vehicles is desired. Vehicle-to-vehicle (V2V) communications enable vehicles to stay connected to each other and react to any exchange of information.

In order to take advantage of V2V upcoming applications, a robust method of communication between vehicles must be established. Accurate and reliable channel estimation is critical to the overall system performance, and in V2V communications the main challenge to system performance is the extremely fast time varying channel characteristics due to vehicular high speeds and the high mobility of the environment including scatterers. That is why trying to enhance the system performance while complying with the IEEE 802.11p standard is very challenging in the highly dynamic V2V environment.

The IEEE 802.11p standard, referred to as Dedicated Short Range Communication (DSRC), is the de facto standard for V2V communications. The DSRC physical layer (IEEE 802.11p) [1] was originally adapted from IEEE 802.11a standard, which uses an OFDM physical layer. Because of the time varying channel nature, coupled with the fact that the 802.11p standard can support large packet lengths, the channel estimate performed at the beginning of each packet can be quickly outdated. In addition, the 802.11p standard only uses four pilot subcarriers in each OFDM symbol. These pilot subcarriers are not spaced close enough to reflect channel variation in the frequency domain. Therefore, the main challenge is to identify an accurate method for updating the channel estimate over the entire packet length using the pilot structure of the standard.

Three channel estimation and tracking algorithms are proposed to deal with the pilot structure of the 802.11p standard as well as V2V channel characteristics. First, we implement a semi-blind channel estimation algorithm benefiting from the finite alphabet property of the transmitted symbols. Second, we propose to use decision directed channel estimation combined with time domain truncation to alleviate some of the effects of error propagation. Third, the pilot information and the high correlation characteristic of the channel response between adjacent subcarriers are exploited.

In [2], several channel estimation schemes were developed to closely track the V2V channel and thus decrease the packet error rate (PER). Through a set of empirical experiments, it was shown that the PER could be decreased using the spectral temporal averaging (STA) instead of the conventional least squares estimator (LS). However, this scheme depends on knowledge of the radio environment that is hard to obtain in practice, so fixed values are used instead which degrades the performance. Also in [3], a dynamic equalization scheme was described that decreases the PER of the V2V communications. The complexity of this scheme is considerably high as decision directed channel estimation is carried out based on feedback from the Viterbi decoder then it goes all the way back through convolutional encoder, bit interleaver, modulation and pilot insertion until a channel estimate could be obtained. This scheme clearly has high latency. In [4], an advanced receiver scheme was proposed that uses decision directed channel estimation complemented with channel smoothing to reach satisfactory performance at the expense of huge increase in computational complexity due to multiplication of large matrices. Moreover, the proposed complexity reduction techniques cause significant performance degradation. On the other hand, in [5] a design of a more efficient physical layer is presented using time domain differential OFDM. Although this technique is suitable for mobile environments, it requires changes in the IEEE 802.11p standard.

The rest of this paper is as follows. In Section II, we describe the V2V system model. In section III, a detailed explanation of our proposed channel estimation algorithms is presented. In section IV, simulation results are presented for performance comparison, and we conclude in section V.

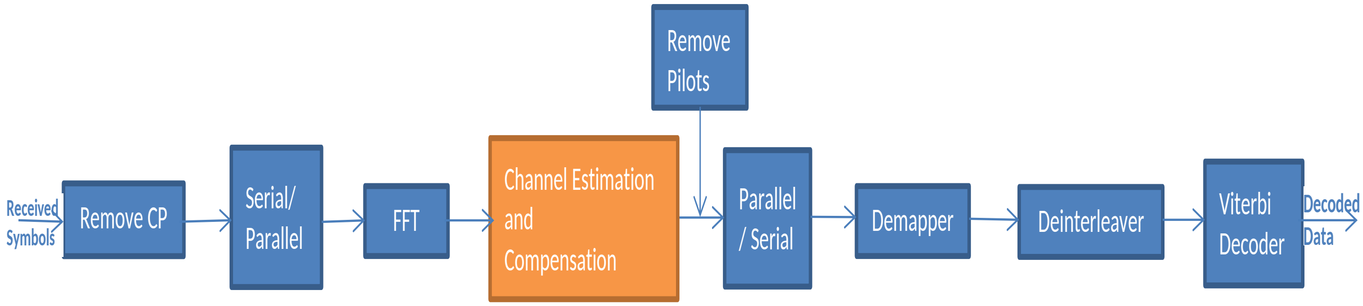

Fig. 1: IEEE 802.11p Receiver Components.

II. System Model

A. Frame Structure and Conventional Least Squares

The design and performance of conventional DSRC systems are discussed in this section. Forward error correction (FEC) coding is used to detect and correct errors due to channel fading and noise. The FEC code that is used in this system is rate 1/2 convolutional code with a generator (133, 171) and constraint length of 7.

The length of the block interleaver corresponds to one OFDM data symbol. The dimension of the block depends on the modulation scheme selected. The interleaved bits are digitally modulated and divided into 48 sub-channels with four fixed pilot tones.

At the receiver, shown in Fig. 1, the cyclic prefix is removed from the received signal. The parallel data are demultiplexed into the FFT, yielding the following output in the frequency domain

$$Y_t(k) = H_t(k)S_t(k) + Z_t(k), \qquad (1)$$

where $Y_t(k)$ and $S_t(k)$ denote the FFT of the received and transmitted OFDM data symbols, respectively, t represents the OFDM symbol index, k represents the subcarrier number, $H_t(k)$ represents the channel response and $Z_t(k)$ represents the additive white Gaussian noise (AWGN). After demultiplexing, the data are compensated, digitally demodulated, deinterleaved and finally decoded using the Viterbi algorithm.

Least squares estimator is used to estimate the channel using the two similar preamble symbols sent before the data symbols at the beginning of each packet. The first two received symbols Y_{P1} and Y_{P2} are divided by the known training sequence X_P then averaged to get the channel estimate for all subcarriers given by

$$\hat{H}_{LS}(k) = \frac{Y_{P1}(k) + Y_{P2}(k)}{2X_P(k)} \qquad (2)$$

where $\hat{H}_{LS}(k)$ is the least squares channel estimate on the k^{th} subcarrier. This estimate may be used to compensate for the channel effects for all the upcoming data symbols in the same packet, if the channel is assumed to be nearly constant throughout the whole packet length. This is not a valid assumption in the case of DSRC as the channel varies significantly from one symbol to another due to fast varying environment dynamics specially at high vehicular speeds.

A conventional WLAN system receiver cannot be applied to vehicular environments, so the receiver has to be modified to incorporate an accurate channel tracking technique.

B. Channel Model

Knowledge of the V2V propagation channel is essential for the design and performance evaluation of the entire V2V system. Therefore, V2V channel measurement campaigns were conducted including the various V2V scenarios. It was found that the V2V channel is different from the popular cellular channels in terms of both frequency and time selectivity as well as the fading statistics.

Due to the high-speed motion of the transmitter, the receiver and the scatterers the V2V channel characteristics are highly time varying as well as the channel impulse response. So in order to have a reliable channel model we have to work with a large sequence of channel impulse responses which is not an easy task to do. That is why several statistical channel metrics were derived to represent a compact channel characterization. Path loss, fading statistics, delay spread and Doppler spread are the main statistical channel metrics.

In our simulations, we adopted the standard 802.11p channel models in [6], where six channel models are defined for different vehicular scenarios as shown in Table I and the type of model we consider is the tapped-delay line, where each tap process is described by a Doppler power spectral density (PSD) having Rayleigh fading and the channel impulse response has 8 taps.

TABLE I: IEEE 802.11p standard channel models

Scenario	Distance between the Tx & Rx (m)	Velocity (Km/hr)	Doppler Shift (Hz)	Excess Delay (μS)
V2V Expressway Oncoming	300-400	104	1000-1200	0.3
V2V Urban Canyon Oncoming	100	32-48	400-500	0.4
RTV Suburban Street	100	32-48	300-500	0.7
RTV Expressway	300-400	104	600-700	0.4
V2V Expressway same direction with wall	300-400	104	900-1150	0.7
RTV Urban Canyon	100	32-48	300	0.5

III. Channel Estimation Techniques

A. Spectral Temporal Averaging (STA)

The STA technique was presented in [2]. STA is based on the correlation between each subcarrier and its neighboring subcarriers in the frequency domain as well as the time correlation between successive OFDM symbols. STA is done as follows. First, the LS estimate $\hat{H}_{LS}$ is used as an initial estimate then data decision feedback is done by demodulating the first data symbol compensated by the LS initial estimate as follows

$$\hat{S}_t(k) = \frac{Y_t(k)}{\hat{H}_{t-1}(k)} \tag{3}$$

where $\hat{S}_t(k)$ is the equalized symbol at subcarrier k and time t, $Y_t(k)$ is the received symbol at subcarrier k and time t and $\hat{H}_{t-1}(k)$ is the channel estimate of the previous symbol. A more accurate channel estimate is calculated using the demodulated data as shown below

$$\hat{H}_t(k) = \frac{Y_t(k)}{\hat{X}_t(k)} \tag{4}$$

where $\hat{X}_t(k)$ is the demodulated symbol from $\hat{S}_t(k)$. The frequency domain correlation between neighboring subcarriers is exploited by the below formula

$$H_{up,\,t}(k) = \sum_{i=-\beta}^{\beta} W_i \hat{H}_t(k+i) \tag{5}$$

where $H_{up,\,t}$ is the updated channel estimate based on the correlation between neighboring subcarriers, β is the window size where the weighted average takes place and W_i is the weight of each subcarrier in the window. Then the time domain averaging is done as follows

$$\mathbf{H}_{STA,\,t} = \left(1 - \frac{1}{\alpha}\right)\mathbf{H}_{STA,\,t-1} + \frac{1}{\alpha}\mathbf{H}_{up,\,t} \tag{6}$$

where α is called the forgetting factor and it is optimized based on the channel characteristics and $\mathbf{H}_{STA,\,t}$ is the estimated channel gain vector using the STA algorithm at time t.

B. Finite Alphabet with Time Truncation (FA-TT)

In our proposed techniques, and their variants, we exploit the pilot information in each OFDM symbol to determine the channel polarity and also the number of channel taps in time domain is exploited to boost the performance using time domain channel truncation.

1) Finite Alphabet (FA): Here, the initial channel estimates are obtained based on the finite alphabet property [7] of the transmitted data symbols; symbols are drawn from a finite alphabet set of size Q. The channel, raised to some power J, can be obtained as follows

$$\hat{H}^J(k) = \gamma \frac{1}{I} \sum_{i=0}^{I-1} Y^J(i;k) \tag{7}$$

where $J = 2$ for BPSK and $J = 4$ for any higher order QAM, γ is a constant used to neutralize the data effect from the channel estimates where γ equals to 1 for BPSK, -1 for QPSK, and so on, and I is the window size. In our algorithm a window size of 3 OFDM symbols is used to decrease the noise effect and also be able to track the fast channel variations. Then, we can get

$$\mathbf{\Phi} = \text{IFFT}(\hat{H}^J). \tag{8}$$

If we ignore the noise, $\hat{H}^J$ is the perfect channel raised to the J^{th} power and the $\mathbf{\Phi}$ is the J-fold convolution of the perfect channel in the time domain so $\mathbf{\Phi}$ could be used as reference in case of noisy channel estimates.

An exhaustive search over all the combinations of any eight equally spaced subcarriers is done in order to get the 8-tap channel in the time domain then a J-fold convolution is calculated and the distance between $\mathbf{\Phi}$ and each of the Q^8 combinations is calculated and the minimum distance will be the initial estimate for our algorithm as shown below

$$\hat{\mathbf{H}}_\mathbf{1} = \lambda_m [\hat{H}^J(k)]^{1/J} \tag{9}$$

where λ_m is the corresponding scalar ambiguity when taking the J^{th} root.

$$\hat{\mathbf{h}}_\mathbf{init} = \arg\min_{\hat{\mathbf{h}}_\mathbf{1}} ||\Phi - \hat{\mathbf{h}}_\mathbf{1} *_J \hat{\mathbf{h}}_\mathbf{1}|| \tag{10}$$

where $\hat{\mathbf{h}}_\mathbf{1} = \text{IFFT}(\hat{\mathbf{H}}_\mathbf{1})$ and $*_J$ denotes the J-fold convolution; then the 8-tap channel estimates $\hat{\mathbf{h}}_\mathbf{1}$ are FFT processed to be converted to 64-subcarrier frequency response.

$$\mathbf{H}_\mathbf{1} = \text{FFT}(\hat{\mathbf{h}}_\mathbf{1}). \tag{11}$$

Majority rule is used to solve the polarity ambiguity of the channel impulse response by comparing the initial channel estimates ($\mathbf{H}_\mathbf{1}$) of the 4 pilot symbols with their LS channel estimates and adjusting the channel polarity accordingly.

2) Time Truncation (TT): In order to exploit the time domain channel characteristics of the V2V environment, time truncation is used to boost the channel estimation and tracking capabilities as well as resolving the phase ambiguities of the channel frequency response. We truncate the channel estimates in the time domain that are higher than the 8^{th} tap defined by the V2V channel model, and then go back and forth between the frequency and time domains until convergence. It was found by simulations that this loop converges after a few iterations, so we choose to fix it at only two iterations. The effect of channel noise, and thus channel estimation error, in the frequency domain are reflected as a higher number of taps in the time domain. That is why truncating the channel impulse response increases the channel tracking capabilities in a highly dynamic environment and enhances channel estimation performance.

The phase ambiguities are resolved by searching over J candidate phase values as follows.

$$H_{freq}(k) = \arg\min_{\lambda_m [\hat{H}^J(k)]^{1/J}} ||H_{freq}(k) - \lambda_m [\hat{H}^J(k)]^{1/J}|| \tag{12}$$

where $H_{freq}(k)$ is the initial channel estimates in the frequency domain and $\hat{H}^J$ is the received signal raised to the J^{th} power to eliminate the effect of data.

$$\mathbf{h_{time}} = IFFT(\mathbf{H_{freq}}) \quad (13)$$

$$\mathbf{H_{freq}} = FFT(\mathbf{h_{time}}(1:8)). \quad (14)$$

Then the pilots majority rule is used again as the channel estimates may converge at the wrong polarity.

The problem with FA-TT algorithm as described is that the computational complexity increases greatly as the modulation order increases which makes it practical only for the BPSK case.

C. Decision Directed with Time Truncation (DD-TT)

In this subsection a novel semi blind channel estimation and tracking algorithm is proposed for highly dynamic V2V environments. In the proposed algorithm, we use decision directed channel estimation to get an initial estimate, then time truncation is performed. An explanation and breakdown of the algorithm is given as follows.

1. We will start with the LS estimate $\hat{H}_{LS}$ as an initial estimate then channel equalization of the first data symbol is done by the LS initial estimate as in (3)

2. A further modification is done using the demodulated data to get a more accurate channel estimates as shown in (4)

3. A much better estimate is obtained using the time truncation technique according to equations (12)-(14).

The reason behind the performance gain is noise cancellation by calculating the initial channel estimate using the demodulated data and also exploiting the pilots' information to determine the channel polarity with a great degree of confidence using the majority rule. Moreover, exploiting the number of taps of the V2V channel model gives the high performance boost to the algorithm. Besides the fact that estimating the channel taps depends only on the channel of the previous symbol as well as the current one makes the algorithm able to track the channels fast variations.

D. Minimum Distance with Time Truncation (MD-TT)

This estimator has a low computational complexity and the ability to track fast channel variations by exploiting the channel estimates at the four pilots in every OFDM symbol as well as the high correlation characteristic of the channel response between adjacent subcarriers.

First the 48 data subcarriers are divided into four groups. Each group has the pilot subcarrier in the middle.

Starting from the pilot position, the channel estimates of the neighboring subcarriers at both sides are determined based on the minimum Euclidean distance between the pilot channel estimate and the possible channel responses of its neighboring subcarrier according to the equations below. Depending on the relative location to the pilot, if the subcarrier is on the right side of the pilot, we use equation (15); otherwise we use equation (16).

We then use the estimated channel response of the neighboring subcarrier to estimate the subcarrier next to it, and so on, until all the neighboring subcarriers in the pilot's group are scanned and then we move on to the following pilot position until all the four groups are scanned and the channel estimates of the 48 data subcarriers are calculated.

$$H_{freq}(k+1) = \arg \min_{\lambda_m[\hat{H}(k+1)]} ||H_{freq}(k) - \lambda_m[\hat{H}(k+1)]|| \quad (15)$$

$$H_{freq}(k-1) = \arg \min_{\lambda_m[\hat{H}(k-1)]} ||H_{freq}(k) - \lambda_m[\hat{H}(k-1)]|| \quad (16)$$

where λ_m is the corresponding ambiguity in the channel response based on the constellation used in data transmission ($\lambda_m \in \{\pm 1\}$ for BPSK and $\lambda_m \in \{\pm 1, \pm j\}$ for QPSK).

To enhance the tracking capabilities of the Minimum Distance Estimator, time truncation is done to exploit the information about the channel taps in the time domain. The Minimum Distance Estimator provides the time truncation algorithm with the initial estimate. Time truncation iterations enable the estimator to track fast channel variations more closely and yet the complexity of the overall estimator is still low. MD-TT achieves the best performance compared to previous channel estimation techniques used for V2V communications.

IV. Simulation Results

DSRC physical layer was simulated using MATLAB. The BER is the performance measure of the system. The initial focus is to test the performance limitations under the worst case scenario, which is a fading channel with no LOS (i.e. Rayleigh fading channel), and maximum Doppler and packet size.

The systems were simulated with varying SNR, velocity, packet lengths and modulation scheme (i.e. data rate). The maximum simulated velocity was 104 km/h. The packet lengths were ranging from 25 to 200 OFDM data symbols per packet.

A thorough comparison between the conventional least squares, the STA algorithm and the proposed designs is presented as BER plots. A plethora of results were produced; however, only few plots are presented as examples without loss of generality.

The figures presented show the BER plots for BPSK, QPSK and 16 QAM, V2V Expressway Oncoming and V2V Urban Canyon Oncoming scenarios with different OFDM symbols per packet ranging from 100 to 200 for BPSK, 50 for QPSK and 25 for 16QAM.

Simulation results showed that the proposed schemes reduce the BER compared to the conventional least squares estimator for all modulation schemes for all channel models and all packet sizes. Fig. 2 through Fig. 5 show the BER performance of the different channel estimation and tracking algorithms. We can clearly see significant performance gains of the proposed DD-TT and MD-TT as compared to the STA algorithm of [2].

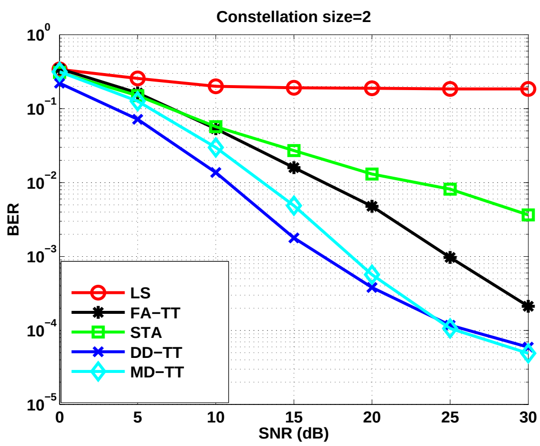

Fig. 2: BPSK Bit Error Rate, maximum doppler=500Hz and 100 OFDM symbol/packet (V2V Urban Canyon Oncoming).

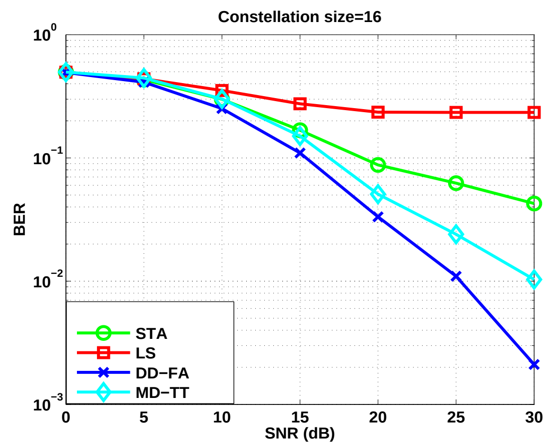

Fig. 5: 16QAM Bit Error Rate, maximum doppler=1000Hz and 25 OFDM symbol/packet (V2V Expressway Oncoming).

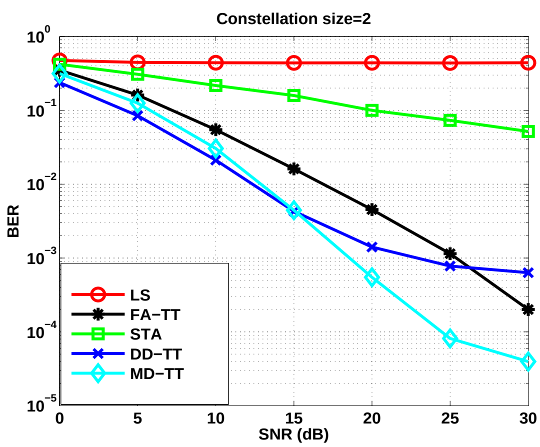

Fig. 3: BPSK Bit Error Rate, maximum doppler=1000Hz and 200 OFDM symbol/packet (V2V Expressway Oncoming).

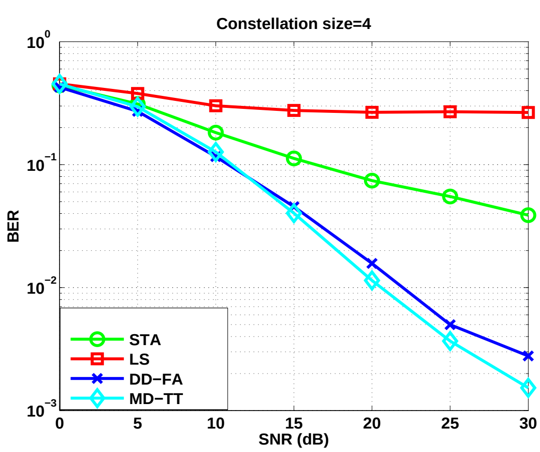

Fig. 4: QPSK Bit Error Rate, maximum doppler=1000Hz and 50 OFDM symbol/packet (V2V Expressway Oncoming).

V. CONCLUSION

In this paper, three channel estimation and tracking algorithms were proposed for the 5.9 GHz DSRC receiver. The algorithms achieve very high performance for low mobile environments as well as fast varying channels, even for large packet sizes. Moreover, both the MD-TT and DD-TT have low computational complexity even for higher constellation sizes, and that is why these two algorithms are the most suitable for implementation. The receivers with DD-TT and MD-TT estimators improved BER performance in all modulation schemes, namely BPSK, QPSK and 16-QAM. The proposed DD-TT and MD-TT schemes were shown to be very effective and practical for WAVE applications, since it is relatively simple and compliant with the IEEE802.11p standard.

REFERENCES

[1] "IEEE standard for information technology– local and metropolitan area networks– specific requirements– part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless access in vehicular environments," *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007)*, pp. 1–51, July 2010.

[2] J.A. Fernandez, D.D. Stancil, and Fan Bai, "Dynamic channel equalization for IEEE 802.11p waveforms in the vehicle-to-vehicle channel," in *Communication, Control, and Computing (Allerton), 2010 48th Annual Allerton Conference on*, Sept 2010, pp. 542–551.

[3] H. Abdulhamid, E. Abdel-Raheem, and K.E. Tepe, "Channel estimation for 5.9 ghz dedicated shortrange communications receiver in wireless access vehicular environments," *Communications, IET*, vol. 1, no. 6, pp. 1274–1279, Dec 2007.

[4] A Bourdoux, H. Cappelle, and A Dejonghe, "Channel tracking for fast time-varying channels in IEEE802.11p systems," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, Dec 2011, pp. 1–6.

[5] Youwei Zhang, Ian L. Tan, Carl Chun, Ken Laberteaux, and Ahmad Bahai, "A differential OFDM approach to coherence time mitigation in DSRC," in *VANET '08 Proceedings of the fifth ACM international workshop on VehicularAr Inter-NETworking*, September 2008, pp. 1102–1105.

[6] G. Acosta-Marum and M.-A. Ingram, "Six time- and frequency- selective empirical channel models for vehicular wireless LANs," *Vehicular Technology Magazine, IEEE*, vol. 2, no. 4, pp. 4–11, Dec 2007.

[7] Shengli Zhou and G.B. Giannakis, "Finite-alphabet based channel estimation for OFDM and related multicarrier systems," *Communications, IEEE Transactions on*, vol. 49, no. 8, pp. 1402–1414, Aug 2001.