Low Complexity Decision–Directed Channel Estimation based on a Reliable–Symbol Selection Strategy for OFDM Systems

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Abstract— This paper presents a low-complexity/low-latency algorithm for estimating and tracking time-varying fading channels in Orthogonal Frequency Division Multiplexing (OFDM) systems. More specifically, it is described a decision directed (DD) channel estimation (CE) method, consisting of two main steps: 1) Data detection of the current received OFDM symbol is performed by using the channel coefficients estimated in correspondence to the previous OFDM symbol; 2) The channel corresponding to the current OFDM symbol is estimated by using a subset of the newly detected data symbols. The data subset, used to perform successive refinement on the channel estimation, is found by choosing the OFDM subcarriers with the highest expected signal-to-noise ratio (SNR). Such a subcarrier selection strategy is robust against the use of incorrect data symbols in the channel estimation process. The extension of the presented technique to multiple receive antennas is also discussed. The proposed estimation method is potentially useful for IEEE 802.11p compliant vehicular communication systems, whose basic modulation parameters are herein used for computer simulation of the information error rate.

I. INTRODUCTION

Vehicle–to–vehicle (V2V) and vehicle–to–infrastructure (V2I) transmissions represent the fundamental communication links to support Intelligent Transportation Systems (ITS) applications. Dedicated Short Range Communications (DSRC) is a short–to–medium range communication service that supports several applications (like driver safety and electronic toll collection) that require very low latency and high data rate. Concerning the physical layer (PHY) of DSRC technologies, most vehicular communication standards under development worldwide will be based on IEEE 802.11p [1]. The PHY of IEEE 802.11p is derived from the popular IEEE 802.11a standard [2] which adopts OFDM as modulation format.

OFDM is a widely used modulation technique that permits robust and efficient data communications in multi-path fading channels. In particular, since multipath propagation in large outdoor environments is generally characterized by longer delay spreads than in indoor channels, [1] specifies the use of half of the bandwidth (10 MHz) than for IEEE 802.11a devices, in order to double the symbol and guard interval (GI) duration, and then limit the effect of inter-symbol interference (ISI).

Channel amplitude and phase signal distortions are time-varying due to the presence of the Doppler spread caused by moving radio equipments and moving objects in the transmission environment, as typical of V2V and V2I communications. Channel estimation schemes designed for IEEE 802.11 a/g/p standards exploit the presence of a known training data sequence in each packet preamble. Moreover, $N_p = 4$ known pilot symbols are inserted in given frequency tone positions of every transmitted OFDM symbol, to enable phase and carrier frequency offset (CFO) tracking and compensation. However, if the channel is time-varying, then the preamble can only be used to perform an initial channel estimation, and, moreover, the only pilot symbols are in general not sufficient to successfully track channel variations occurring during the duration of a single packet. Hence, OFDM systems originally designed for indoor use suffer severe performance degradations induced by the channel Doppler spread and their application to mobile communication systems requires the design of receivers with enhanced features.

This paper is concerned with a channel estimation technique able to track channel variations by means of some estimated demodulated data symbols, thus falling into the class of decision directed (DD) channel estimators. In particular, data recovery for the purpose of channel estimation is done without the aid of forward error correction (FEC) decoding, but by simple hard data detection (HDD), thus resulting in a low-complexity and low-latency, yet pretty well performing, technique. If time variations are fast, then wrong data estimation may cause error propagation in channel updates on successive OFDM symbols. It is shown that such a drawback can be mitigated by using a symbol selection algorithm (SSA), working on some reliability coefficients, that discard those detected symbols that are judged unreliable. We also show that the resulting DD algorithm can be extended for use with multiple receive antennas.

Several DD CE techniques have been treated in literature in the past years. The present work differentiates from [3], [4] as no FEC decoder is used in the data estimation loop, thus resulting in a much lower complexity and latency. The issue of error propagation is also the subject of several works, see for instance [5] and references therein. However, compared to those works our proposal is significantly simpler, though in all cases no FEC decoder is employed, as we do not require the collection of robust statistics to compute the decision weights. It should also be mentioned the work of [6], wherein HDD to re-estimate data is used and their reliability estimated. However their reliability coefficient (RC) is SNR-based, thus dependent on the employed modulation order, and
no mention is made about a minimum number of symbols to be selected regardless of their reliability (linked to the time domain channel length) nor possible extension to multiple receive antennas.

The rest of the paper is organized as follows. In Section II the system notation is introduced. In Section III the proposed DD channel estimation method is described, and Section III-A describes the SSA. Section IV discusses the obtained simulation results. Finally, the paper is concluded in Section V.

II. SYSTEM MODEL

We consider an OFDM system characterized by the following parameters: $B$ is the transmission bandwidth; $M$ the number of sub-carriers; $L_{cp}$ the number of samples used for the guard interval (GI) (cyclic extension) appended to each OFDM symbol. Therefore, $T_c = 1/B$ is the channel sampling time and the duration of an OFDM symbol results $T = (M + L_{cp})T_c$.

First, we deal with the case of a single receive antenna. The point-to-point multipath wireless link is modeled as a time-varying wide sense stationary-uncorrelated scattering random process, where the discrete-time channel impulse response (CIR), with $T_c$ spaced taps, at time $kT$, is given by

$$ h(kT, nT_c) = \sum_{l=0}^{L_{ch} - 1} \alpha_l(kT) \delta(nT_c - lT_c), \quad (1) $$

where $L_{ch}$ is the number of channel taps at time instant $kT$. The path gains $\alpha_l(kT)$ are zero-mean complex Gaussian random variables with statistical power $\sigma_l^2 = \mathbb{E}[|\alpha_l(kT)|^2]$, $l = 0, 1, \ldots, L_{ch} - 1$. Note that the model (1) implicitly assumes that the channel remains static within the duration of one OFDM symbol but it may change for successive symbols according to a given Doppler spectrum $D(f)$. With this assumption no inter-carrier interference (ICI) is present: it can actually be shown that the ICI contribution can be well approximated through a SNR degradation, which is anyway negligible for relative vehicle speed of up to $v = 200 \text{km/h}$.

The information data column vector at time $kT$ is

$$ \mathbf{A}_k = [A_{k,0}, A_{k,1}, \ldots, A_{k,M-1}]^T, \quad (2) $$

where the symbol $A_{k,m}$ belongs to a fixed PSK/QAM constellation and it is loaded on the $m$-th OFDM subcarrier.

We assume perfect time-frequency synchronization and removal of the cyclic prefix at the receiver. Moreover, assuming

$$ L_{ch} \leq L_{cp}, \text{ no ISI is present and then the M-entry OFDM demodulated signal } Y_k, \text{ at time instant } kT, \text{ can be written as} $$

$$ Y_k = D_k \mathbf{H}_k + \mathbf{N}_k, \quad (3) $$

where $D_k$ is a $M \times M$ diagonal matrix having the elements of $\mathbf{A}_k$ on its diagonal: $D_k = \text{diag} \{A_k\}$; $\mathbf{H}_k = [H_{k,0}, H_{k,1}, \ldots, H_{k,M-1}]^T$ is the vector of the $M$ channel frequency response (CFR) coefficients at time $kT$, with elements $H_{k,m} = \sum_{l=0}^{L_{ch} - 1} \alpha_l(kT) e^{-j 2\pi l \Delta f}$; the term $\mathbf{N}_k = [N_{k,0}, N_{k,1}, \ldots, N_{k,M-1}]^T$ represents additive white Gaussian noise (AWGN) with statistical power $\sigma_n^2$.

In the following, reference is made to possible implementations of transmitters and receivers compliant to IEEE 802.11p [1], see Figs. 1 and 2. The DD channel estimation techniques proposed in the next section can be seen as a key feature of the enhanced IEEE 802.11p receivers.

III. DECISION DIRECTED CHANNEL ESTIMATION USING HARD DATA DETECTION

The proposed DD channel estimation and tracking technique consists of the following two successive steps.

1. Hard estimation $\hat{\mathbf{A}}_k$ of the complex data vector $\mathbf{A}_k$ by means of the estimated channel coefficients $\mathbf{H}_{k-1}$, obtained from the previous OFDM symbol.

2. New channel estimation $\mathbf{H}_k$ by using pilot and a subset of the detected information symbols $\hat{\mathbf{A}}_k$.

The DD technique requires an initial CE that is used to demodulate the first received OFDM data symbol. In this paper reference will be made to the structure of the frame specified by [1], [2]. The packet is given by a preamble followed by a signal field and a data field. Part of the preamble is composed by a sequence of known training symbols used for initial CE. The data field contains a variable number of OFDM symbols (payload) to be transmitted.

Since we are dealing with a time-varying transmission link, the estimation of the CIR is kept up-to-date by exploiting
both pilot symbols and some of the data symbols estimated from the payload. We note that \( N_p \) pilot symbols are not sufficient to estimate channels of length \( L_{ch} > N_p \). Moreover, with a higher number of known symbols a larger estimation processing gain can be obtained, provided that the introduced estimated symbols are correct.

In more detail, the main steps of the proposed DD algorithm are the following:

1. Data estimation of the \( k \)-th OFDM symbol, \( \hat{A}_k = [\hat{A}_{k,0}, \hat{A}_{k,1}, \ldots, \hat{A}_{k,M-1}] \), is first performed through HDD by using the CFR \( \hat{H}_{k-1} \) estimated in correspondence to the \( (k-1) \)-th OFDM symbol. For example with Zero Forcing Equalization (ZFE) we find

\[
\hat{A}_{k,m} = \text{TD}\{Y_{k,m}\hat{H}_{k-1,m}^{-1}\}, \quad m \in S_d,
\]

where \( \text{TD}\{\cdot\} \) represents threshold decision (i.e., slicing to the closest constellation symbol) and \( S_d \) is the set of data sub-carrier indexes.

It is intended that any other HDD equalization method, such as minimum mean square error (MMSE), might be used without limiting the generality of the proposed algorithm.

2. The CFR \( \hat{H}_{k} \) corresponding to the \( k \)-th OFDM symbol, which is possibly changed compared to \( \hat{H}_{k-1} \), because of the time-varying channel, is estimated by using \( \hat{D}_k = \text{diag}\{\hat{A}_k\} \), i.e., using the newly detected information symbols which are then added to the known pilot symbols (if any) to form an extended known data matrix.

Then, the updated CFR \( \hat{H}_k \) at time \( kT \) is stored and used at the reception of the \( (k+1) \)-th OFDM symbol to start a new iteration of the algorithm. At the same time, as shown in Fig. 2, \( \hat{H}_k \) is used by the equalizer to demodulate the \( k \)-th received OFDM symbol and output the corresponding estimated data vector \( \hat{A}_k \) prior to proceeding with soft bit generation and FEC decoding to recover the final information bits.

An important problem to consider is the error propagation in case of incorrect data detection. In fact, hard symbol detection is performed with an error rate equal to the uncoded symbol error rate, since estimation is performed right after OFDM demodulation, before decoding. Moreover, besides the noise contribution, errors occur because of the use of an out-of-date channel estimation \( \hat{H}_{k-1} \). Therefore, to face this problem a Symbol Selection Algorithm (SSA) is proposed, in order to down-select a subset \( \mathcal{S} \) of the most reliable data symbols, i.e., data symbols that might be correct with high probability, modulating the data subcarriers. Such algorithm aims to avoid estimation accuracy degradation due to the use of incorrect data symbols in the CE process.

### A. Symbol selection algorithm

The idea is to associate a RC to each received data symbol: symbols with the highest RCs are more likely to be correct and then they are assumed to be reliable.

The proposed RC is simply given by

\[
\Psi_{k,m} = |\hat{H}_{k-1,m}|^2.
\]

An intuitive explanation of why this is a good metric can be found recalling that both the uncoded symbol error rate (SER) and the mutual information for OFDM sub-channel depend on the squared envelope of the CFR \( H_{k-1,m} \), which determines the instantaneous SNR on each OFDM subcarrier.

The selection of the most reliable symbols, to be used to perform channel tracking, reduces possible CE propagation errors caused by wrongly detected symbols. The SSA defines a threshold \( \Psi_{thr} \) such that symbols for which \( \Psi_{k,m} > \Psi_{thr} \) are considered reliable. Simulation results reported in Sect. IV show that, although an optimal threshold depends on modulation and channel parameters, good simulation performance can be obtained through the heuristic choice of a fixed \( \Psi_{thr} \) for a wide set of transmission scenarios of interest.

A pseudo-code description of the SSA is the following.

1. The \( N_p \) pilot symbols are known and then they are all inserted in the set of chosen symbols \( \mathcal{S} \).
2. Compute the \( \Psi_{k,m} \) for all the \( S_d \) OFDM data carrier index set in an OFDM symbol.
3. For every \( m \in S_d \) check if \( \Psi_{k,m} > \Psi_{thr} \):
   - if true, then include the \( m \)-th data symbol in \( \mathcal{S} \);
   - if false, then discard it.
4. If the dimension \( N_s \) of the set \( \mathcal{S} \) is \( N_s = N_d + N_p \leq L_{ch} \), \( N_p \) being the number of selected data subcarriers, then insert in the selected set the \( L_{ch} - N_s \) symbols having the highest associated RC among the previously discarded symbols. This implies keeping an ordered list of the RCs.

To summarize, the block diagram of the proposed iterative DD CE algorithm is illustrated in Fig. 3 and consists of the following steps, to be repeated prior to the demodulation of every received OFDM symbol:

1. RC association (RCA) through the metric (5) computed using the CFR stored at the previous time instant.
2. Data SSA using the RCs computed at step 1.
3. Data sub-carrier PSK/QAM symbol estimation through HDD (for instance either ZF or MMSE can be used for channel equalization).
4. Estimation of the channel at the current time instant.

It should finally be noted that different CE methods for OFDM systems can be used for the described DD CE algorithm (see [8] for a complete survey on this topic).

Simulations shown in this paper used the reduced-rank least-square (rr-LS) criterion [9]. Assuming \( M \gg L_{ch} \), a CIR length-cognizant estimator has provably better performance

![Fig. 3. Block diagram of DD CE with SSA](image-url)
in terms of mean squared error with respect to frequency
domain-based approaches, due to the reduced dimension of the set of unknown coefficients to estimate. On the other hand, an estimate of the current CIR length has to be available at the receiver side. The estimation of $L_{ch}$ can be accomplished during the preamble processing by employing, for example, the algorithm proposed in [10], [11]. In absence of an estimate $\hat{L}_{ch}$ of the CIR length, it is possible to simply set $\hat{L}_{ch} = L_{cp} < M$.

B. Single-Input Multiple-Output systems

The DD method introduced in Sect. III can be extended for receivers equipped with multiple $N_r$ receive antennas, i.e., single-input multiple-output (SIMO) systems.

The SIMO DD CE and tracking technique consists of the following two main steps.

1. Data estimation $\hat{A}_k$ of the $k$-th received OFDM symbol is first performed through maximal ratio combining (MRC)

$$\hat{A}_{k,m} = \text{TD} \left\{ \frac{r \sum_{r,k} N_r y_{r,k,m} \hat{H}_{r,k-1,m}}{r \sum_{r,k} |\hat{H}_{r,k-1,m}|^2} \right\},$$

where indexes $r, k, m$ refer, respectively, to the receive antenna, the time instant and the OFDM sub-carrier. It is intended that other equalization and combining methods might be used.

2. The CFRs corresponding to the $k$-th OFDM symbol $\hat{H}_{r,k}$ for each $r$-th antenna, which possibly changed compared to $\hat{H}_{r,k-1}$ because of the time-varying channel, are re-estimated by exploiting the newly detected data plus pilot symbols.

In case of SIMO systems the presented SSA algorithm has to be modified in terms of the considered RC. In particular, the RC associated to a given sub-carrier can be computed using at least two preferred alternative measures:

a) RC based on the sum of the square magnitude of the channel coefficients over the receive antennas

$$\Psi_{k,m} = \sum_{r=1}^{N_r} |\hat{H}_{r,k-1,m}|².$$  

b) Consider the best square magnitude channel coefficient among the $N_r$ receive links

$$\Psi_{k,m} = \max_r |\hat{H}_{r,k-1,m}|².$$  

Both methods (7) and (8) showed similar performance while testing the algorithms and then they are both feasible solutions.

Once the RCs are computed, the SSA presented in Sect. III-A does not need to be modified with respect to the configuration with a single receive antenna, and then Fig. 3 is also representative of the SIMO SSA block diagram.

IV. SIMULATION RESULTS

This section reports the floating point computer simulations of the overall IEEE 802.11p transmission chain.

The ETSI HIPERLAN2 channel models [12] have been selected as representative propagation scenarios. In particular, we considered the models C (NLOS conditions and 150 ns average rms time delay spread) and D (LOS conditions and 140 ns average rms time delay spread). In all cases statistically independent per tap Jakes Doppler spectrum has been used to simulate the time-varying behavior of the channel.

The proposed DD CE with SSA (in the legend of the figures, rr-LS SSA) is compared to the ideal benchmark given by perfectly known channel state information (CSI) at the receiver. Moreover, the case of DD CE employing all data symbols (rr-LS all data) is also shown in order to evaluate the effect of error propagation in the data-aided schemes. Concerning SSA, the results correspond to a fixed threshold value $\psi_{thr} = 0.01$ obtained through to ad-hoc computer simulation tuning.

Additional simulation settings to be mentioned are: 10 MHz bandwidth; 5.9 GHz carrier frequency; perfect time and frequency synchronization; CIR length estimated at the receiver through [11]; rr-LS CIR estimation [9].

Figures 4-7 report the performance of an IEEE 802.11p transceiver employing different CE algorithms, in terms of WLAN packet error rate (PER) versus SNR for different packet lengths ($L$) given in bytes, relative speed between transmitter and receiver ($v$), QAM modulation type, code rate (CR). In particular, the results show that SSA proves to be advantageous for $v \geq 120$ km/h and medium to high packet lengths ($L = 400$ or $L = 2000$) (see Figs. 5-7), while the performance of “rr-LS SSA” and “rr-LS all data” is comparable for $v = 60$ km/h as shown in Fig. 4 and independently of speed for short packets like $L = 50$ bytes (not shown in this paper for the sake of compactness). Incidentally, with no channel tracking the PER is close to one for any SNR.

Finally, Fig. 8 reports an example of the performance of a system employing $N_r = 2$ receive antennas. In this case a good performance can be obtained even for very high speed like $v = 200$ km/h and long packet such as $L = 2000$ bytes, thanks to the exploitation of receive diversity.

V. CONCLUSIONS

This paper describes a low-complexity decision directed channel estimation and tracking algorithm potentially useful for oncoming vehicular communication OFDM-based devices. The proposed technique makes use of hard symbol decisions to re-estimate the channel and, as such, it is characterized by low-complexity and low-latency compared to FEC decoding aided DD CE schemes. The selection of reliable symbols based on some observable quantities helps to reduce error propagation effects due to possible incorrect hard decisions. For complexity reasons, in view of an hardware implementation, the selection of a global threshold for all system configuration has been investigated, although alternative adaptive threshold techniques are under evaluation considering the basis of the specific modulation parameters for a given transmission mode.

REFERENCES

Fig. 4. PER vs. SNR for ETSI C - $v=60$ Km/h, 16QAM CR=1/2, $L=400$

Fig. 5. PER vs. SNR for ETSI C - $v=120$ Km/h, 16QAM CR=1/2, $L=400$

Fig. 6. PER vs. SNR for ETSI C - $v=120$ Km/h, QPSK CR=1/2, $L=2000$

Fig. 7. PER vs. SNR for ETSI D - $v=120$ Km/h, QPSK CR=1/2, $L=2000$

Fig. 8. PER vs. SNR for $N_r=2$, ETSI C - $v=200$ Km/h, 16QAM CR=1/2, $L=2000$


