Time-frequency training OFDM

L. Dai and Z. Wang

A novel transmission scheme called time-frequency training OFDM (TFT-OFDM) is presented, whereby time-domain training sequence and frequency-domain grouped pilots are used for the joint time-frequency channel estimation. The pilots only occupy about 1% of the used subcarriers, and the complex interference cancellation could be avoided. As a result, TFT-OFDM simultaneously achieves high spectral efficiency and reliable performance over fast fading channels.

Introduction: As the key technology of the Chinese national digital television terrestrial broadcasting (DTTBB) standard, time domain synchronous OFDM (TDS-OFDM) has higher spectral efficiency than cyclic prefix OFDM (CP-OFDM) owing to the replacement of CP by the known time-domain training sequence (TS) [1]. However, TDS-OFDM suffers from some performance loss over fast fading channels, but the obviously decreased spectral efficiency is unavoidable.

In this Letter, the time-frequency training OFDM (TFT-OFDM) scheme [4] could realise good performance over fast fading channels with those pilots have high average power. The dual-PN OFDM (DPN-OFDM) scheme [4] could realise good performance over fast fading channels owing to the indispensable iterative inter-block-interference (IBI) cancellation, but the obviously decreased spectral efficiency is unavoidable.

For simplicity, the known time-domain training sequence (TS) [1] is assumed. Therefore,

\[
X_i \quad \text{for } 0 \leq i \leq M-1
\]

is an arbitrary real number.

System model: As shown in Fig. 1, unlike CP-OFDM or TDS-OFDM where the training information exists only in either the frequency or the time domain, the proposed TFT-OFDM uses the TS in the time domain and the small amount of grouped pilots in the frequency domain. The \( i \)th TFT-OFDM symbol is composed of the known TS \( c_i \in \mathbb{C} \), data subcarriers and \( N_p \) pilots composed of \( N_{\text{group}} \) scattered pilot groups. Each pilot group has 2 \( BPSK \) modulated pilots, thus \( N_p = N_{\text{group}} (2d+1) \), and \( N = N_p + N_d \). The index set of the central pilot within each group can be denoted by \( \eta = \{ \eta_0, \eta_1, \ldots, \eta_{N_{\text{group}}-1} \} \). It is preferred that the TS has a constant envelope in the frequency domain, i.e., \( C_i = F_{\text{FFT}} \), where \( C_i = \{ C_{i0}, C_{i1}, \ldots, C_{iM-1} \} \) with the entry \( |C_{ik}| = c \) for \( 0 \leq k \leq M-1 \), and \( c \) is an arbitrary real number. For simplicity, \( c = 1 \) is assumed. Therefore, \( c \) has perfect autocorrelation.

The received OFDM block \( Y_i = [Y_{i0}, Y_{i1}, \ldots, Y_{iN-1}]^T \) can be expressed as [5]

\[
Y_i = H_i X_i + W_i
\]

where \( W_i \) is the additive white Gaussian noise (AWGN), \( H_i \) is the channel frequency response matrix with the \( (p+1, q+1) \)th entry \( H_{p,q} \) being

\[
H_{p,q} = \sum_{l=0}^{L-1} \frac{h_{p,q}}{N} e^{-j2\pi N} q_{nl} N_{\text{group}}^2 \frac{e^{-j2\pi N}}{N} q_{nl} N_{\text{group}}^2
\]

where \( h_{n,l} \) denotes the coefficient of the \( n \)th path at the time instant of \( n \) within the \( \text{OFDM block} \), \( q_{nl} \) is the delay of the \( n \)th path, and \( L \) is the number of the resolvable paths. It is clear from (2) that the time delay profile \( \{q_{n}\} \) and the path coefficients \( h_{n,l} \) of the channel have to be accurately estimated for data detection.

Joint time-frequency channel estimation: As shown in Fig. 1, the channel estimation of the proposed TFT-OFDM scheme is achieved by jointly using the time-domain TS and frequency-domain grouped pilots.

1. TS-based path delay estimation: Because of the perfect autocorrelation of the TS, the rough channel estimate \( \hat{h}_i \) can be obtained by circular correlation between the ‘contaminated’ TS and the local TS pre-defined power threshold. As shown in Fig. 2 where the Brazil D channel [2] with signal-to-noise ratio (SNR) of 5 dB is taken as an example, the absence of IBI removal would considerably affect the estimation accuracy of \( \hat{h}_i \), but the path delay information of the actual channel \( h_i \) is preserved well by the rough channel estimate \( \hat{h}_i \).

2. Pilot-based path coefficient estimation: For fast fading channels which vary within every data block, the path coefficient \( h_{n,l} \) in (2) can be modelled by the \( Q \)-order Taylor series expansion [5]

\[
h_{n,l} = \theta_0 + \sum_{q=0}^{Q-1} \rho_q h_{q,l} + \varepsilon_{n,l}
\]

where \( \theta_0 = [1, n, n^2, \ldots, n^Q]_r (Q+1) \), \( \rho_q = [\rho_{q,1}, \rho_{q,2}, \ldots, \rho_{q,Q}]_r (Q+1) \) denotes the polynomial coefficient, and \( \varepsilon_{n,l} \) is the approximation error.

Since the inter-carrier-interference (ICI) is dominantly caused by the neighbouring subcarriers, it can be assumed that the ICI coefficient \( H_{p,q} = 0 \) if \( |p-q| > d \). Thus, the received central pilots \( Y_{i,q} = [Y_{i,q}, Y_{i,q+1}, \ldots, Y_{i,q+N_{\text{group}}-1}]^T \) within the pilot groups can be calculated by

\[
Y_{i,q} = \mathbf{A}_q \theta_q + \xi_q
\]

where \( \xi_q \) is the noise term, \( \mathbf{A}_q = [A_{1,0}, A_{1,1}, \ldots, A_{1,N-1}, A_{2,0}, A_{2,1}, \ldots, A_{2,N-1}, \ldots, A_{Q,0}, A_{Q,1}, \ldots, A_{Q,N-1}]^T \) has the entry \( A_{q,s,l,k} = \frac{1}{N} \sum_{p=0}^{N-1} e^{-j2\pi p(sN+q-l)} \), and \( \theta_q = [\theta_q, \theta_q, \ldots, \theta_q]_r (Q+1) \) has the entry \( \theta_{q,s} = [\theta_{q,0}, \theta_{q,1}, \ldots, \theta_{q,Q}]_r (Q+1) \). Since \( \mathbf{p}_q \) has \( (Q+1)M \) unknown parameters, \( N_{\text{group}} \geq (Q+1)L \) is necessary to guarantee the matrix \( \mathbf{A}_q \theta_q \) to be of full column rank.
Thus, we estimate \( \mathbf{\rho} \) as

\[
\mathbf{\rho} = Y_d = (\mathbf{\beta}_r^H \mathbf{\beta}_r)^{-1} \mathbf{\beta}_r^H Y_p
\]

where \((\cdot)^\dagger \) denotes the Moore-Penrose inverse matrix. Then, the path reconstruction of the received OFDM block can be achieved according to [6]. Thus, the iterative ICI cancellation method [5] can be used to eliminate the dominant ICI terms caused by adjacent \( d \) subcarriers for more reliable zero-forcing channel equalisation.

Once the channel estimation has been obtained, the cyclic prefix reconstruction of the received OFDM block can be achieved according to [6]. Thus, the iterative ICI cancellation method [5] can be used to eliminate the dominant ICI terms caused by adjacent \( d \) subcarriers for more reliable zero-forcing channel equalisation.

**Spectral efficiency:** Only \( N_p = (Q + 1)2d + 1 \) pilots are required in TFT-OFDM, while it has been shown that \( Q = 1, d = 1 \) can already provide satisfactory performance over fading channels, and normally \( L \leq 6 \) can be assumed [5]. So the normalised spectral efficiency of TFT-OFDM is \( \frac{N}{M} \). For typical terrestrial digital television scenarios, the parameter of \( N = 4096 \) is used, and only \( N_p = 36 \) pilots occupying less than 1% of the total subcarriers are required in each TFT-OFDM symbol. On the contrary, the Karhunen-Loeve theorem [5] requires \( M \) pilots for each CP-OFDM symbol, and normally, \( M \gg N_p \). Table 1 compares the spectral efficiency of TFT-OFDM with that of other conventional solutions. It is clear that although TFT-OFDM has marginally lower spectral efficiency than TDS-OFDM due to the sparsely inserted grouped pilots, it has obvious higher efficiency than CP-OFDM and DPN-OFDM.

**Simulation results:** The uncoded system is used for simulation, the signal bandwidth is 7.56 MHz, and the carrier frequency is 770 MHz. The modulation scheme is QPSK. The parameters \( N_p = 36, Q = 1, L = 6 \), and \( M = 512, N = 4096 \) are used. Brazil D channel model [2] is adopted with the receiver velocity of 140 km/h. For fair comparison, the ideal carrier and timing synchronisation are assumed for all the simulated schemes, since the widely investigated synchronisation methods are assumed for all the simulated schemes, since the widely investigated synchronisation methods. For typical terrestrial digital television scenarios, the parameter of \( N = 4096 \) is used, and only \( N_p = 36 \) pilots occupying less than 1% of the total subcarriers are required in each TFT-OFDM symbol. On the contrary, the Karhunen-Loeve theorem [5] requires \( M \) pilots for each CP-OFDM symbol, and normally, \( M \gg N_p \). Table 1 compares the spectral efficiency of TFT-OFDM with that of other conventional solutions. It is clear that although TFT-OFDM has marginally lower spectral efficiency than TDS-OFDM due to the sparsely inserted grouped pilots, it has obvious higher efficiency than CP-OFDM and DPN-OFDM.

**Table 1: Spectral efficiency comparison**

<table>
<thead>
<tr>
<th>Guard interval</th>
<th>CP-OFDM</th>
<th>TDS-OFDM</th>
<th>DPN-OFDM</th>
<th>TFT-OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M = N/4 )</td>
<td>60.00%</td>
<td>80.00%</td>
<td>66.67%</td>
<td>79.30%</td>
</tr>
<tr>
<td>( M = N/8 )</td>
<td>77.78%</td>
<td>88.89%</td>
<td>80.00%</td>
<td>87.52%</td>
</tr>
<tr>
<td>( M = N/16 )</td>
<td>88.23%</td>
<td>94.12%</td>
<td>88.89%</td>
<td>92.59%</td>
</tr>
</tbody>
</table>

**Conclusion:** A novel OFDM-based transmission scheme called TFT-OFDM is proposed, where the training information exists in both the time and the frequency domains. The corresponding joint time-frequency channel estimation naturally avoids the conventional iterative IBI cancellation algorithm and improves the tracking capability of the channel variation. Compared with the conventional solutions, it is shown that higher spectral efficiency as well as better BER performance over fast fading channels can be achieved by the proposed TFT-OFDM scheme.

**Acknowledgments:** This work was supported in part by Chinese AQSIO Project 200910244 and in part by the Tsinghua University Initiative Scientific Research Program 20091081280.

© The Institution of Engineering and Technology 2011
1 September 2011
doi: 10.1049/el.2011.2643

One or more of the Figures in this Letter are available in colour online.

L. Dai and Z. Wang (Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, People’s Republic of China)

E-mail: dli07@mails.tsinghua.edu.cn

References