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 (DTTB) 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 owing to the indispensable iterative inter-block-interference (IBI) cancellation between the TS and OFDM symbol [2]. This issue can be partly solved by inserting redundant pilots to generate the TS [3], but those pilots have high average power. The dual-PN OFDM (DPN-OFDM) scheme [4] could realise good performance over fast fading channels, but the obviously decreased spectral efficiency is unavoidable. In this Letter, the time-frequency training OFDM (TFT-OFDM) scheme is proposed to achieve high spectral efficiency as well as reliable reception over fast time-varying channels.

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 ith TFT-OFDM symbol is composed of the known TS $\mathbf{c}_i = [c_{i,0}, c_{i,1}, \ldots, c_{i,M-1}]^T$ and the OFDM data block $\mathbf{x}_i = [x_{i,0}, x_{i,1}, \ldots, x_{i,N-1}]^T$. Let $\mathbf{X}_i$ be the frequency-domain data, we have $\mathbf{X}_i = \mathbf{F}_N\mathbf{x}_i$, where $\mathbf{F}_N$ denotes the $N \times N$ fast Fourier transform (FFT) matrix. $\mathbf{X}_i$ contains N_d data subcarriers and N_p pilots composed of N_{group} scattered pilot groups. Each pilot group has $2d + 1$ BPSK modulated pilots, thus $N_p = N_{group}\ (2d + 1)$, and $N = N_d + N_p$. The index set of the central pilot within each group can be denoted by $\boldsymbol{\eta} = \{\eta_0, \eta_1, \ldots, \eta_{N_{group}-1}\}$. It is preferred that the TS has a constant envelope in the frequency domain, i.e. $\mathbf{C}_i = \mathbf{F}_M\mathbf{c}_i$, where $\mathbf{C}_i = [C_{i,0}, C_{i,1}, \ldots, C_{i,M-1}]^T$ with the entry $|C_{i,k}| = c$ for $0 \le k \le M - 1$, and c is an arbitrary real number. For simplicity, $c = 1$ is assumed. Therefore, $\mathbf{c}_i$ has perfect autocorrelation.

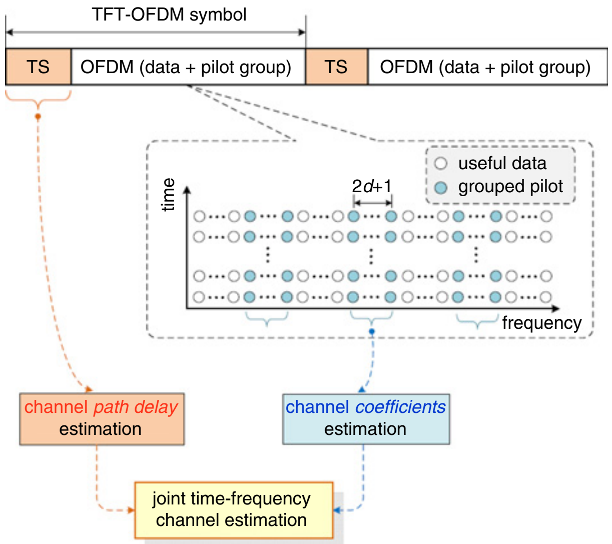

Fig. 1 *Proposed signal structure and corresponding joint time-frequency channel estimation of TFT-OFDM scheme*

The received OFDM block $\mathbf{Y}_i = [Y_{i,0}, Y_{i,1}, \ldots, Y_{i,N-1}]^T$ can be expressed as [5]

$$\boldsymbol{Y}_i = \boldsymbol{H}_i\boldsymbol{X}_i + \boldsymbol{W}_i \tag{1}$$

where $\mathbf{W}_i$ is the additive white Gaussian noise (AWGN), $\mathbf{H}_i$ is the channel frequency response matrix with the $(p + 1,\ q + 1)$th entry $H_{i,p,q}$ being

$$\begin{aligned} H_{i,p,q} &= \sum_{l=0}^{L-1} H_l^{(p,q)} e^{-j\frac{2\pi}{N}qn_l} \\ &= \sum_{l=0}^{L-1}\left(\frac{1}{N}\sum_{n=0}^{N-1} h_{i,n,l}e^{-j\frac{2\pi}{N}n(p-q)}\right)e^{-j\frac{2\pi}{N}qn_l} \end{aligned} \tag{2}$$

where $h_{i,n,l}$ denotes the coefficient of the lth path at the time instant of n within the ith OFDM block, n_l is the delay of the lth path, and L is the number of the resolvable paths. It is clear from (2) that the time delay profile $\{n_l\}_{l=0}^{L-1}$ and the path coefficients $h_{i,n,l}$ 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 $\hat{\mathbf{h}}_i$ can be obtained by circular correlation between the 'contaminated' TS and the local TS without IBI cancellation used in TDS-OFDM. Then, the path delay information is achieved by $\boldsymbol{\Gamma} = \{n_l : |\hat{h}_{i,l}|^2 \ge P_{th}\}_{l=0}^{L-1}$, where P_{th} is the predefined 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 $\hat{\mathbf{h}}_i$, but the path delay information of the actual channel $\mathbf{h}_i$, is preserved well by the rough channel estimate $\hat{\mathbf{h}}_i$.

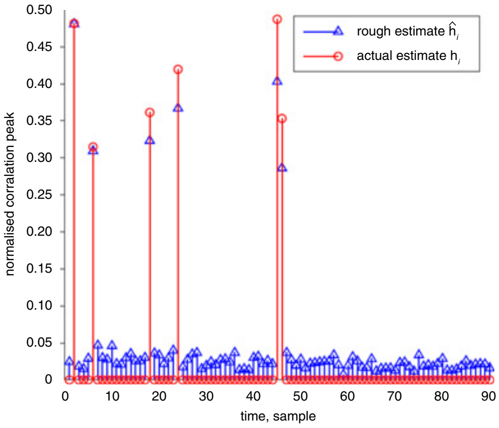

Fig. 2 *TS-based path delay estimation without interference cancellation*

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

$$h_{i,n,l} = \boldsymbol{\theta}_n\boldsymbol{\rho}_{i,l} + \varepsilon_{i,n,l} \tag{3}$$

where $\boldsymbol{\theta}_n = [1,\ n,\ n^2,\ \ldots,\ n^Q]_{1\times(Q+1)}$, $\boldsymbol{\rho}_{i,l} = [\rho_{i,l,0},\ \rho_{i,l,1},\ \ldots,\ \rho_{i,l,Q}]^T_{(Q+1)\times 1}$, $\rho_{i,l,q}$ denotes the polynomial coefficient, and $\varepsilon_{i,n,l}$ 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 $H_{i,p,q} = 0$ if $|p - q| > d$. Thus, the received central pilots $\mathbf{Y}_p = [Y_{i,\eta_0}, Y_{i,\eta_1}, \ldots, Y_{i,\eta_{N_{group}}-1}]^T_{N_{group}\times 1}$ within the pilot groups can be calculated by

$$\mathbf{Y}_p = \boldsymbol{\Lambda}_i\boldsymbol{\theta}_i\boldsymbol{\rho}_i + \xi_i \tag{4}$$

where ξ_i is the noise term, $\boldsymbol{\Lambda}_i = [\boldsymbol{\lambda}_{i,0,0,\eta_0}, \ldots \boldsymbol{\lambda}_{i,N-1,L-1,\eta_0}, \boldsymbol{\lambda}_{i,0,0,\eta_1}, \ldots, \boldsymbol{\lambda}_{i,N-1,L-1,\eta_{N_{group}-1}}]^T_{N_{group}\times LN}$ has the entry $\lambda_{i,n,l,k} = \frac{1}{N}\sum_{q=k-d}^{k+d} e^{-j(2\pi/N)n(k-q)} e^{-j(2\pi)/Nqn_l}X_{i,q}$, $\boldsymbol{\theta}_i = [\boldsymbol{\theta}^T_{i,0}, \boldsymbol{\theta}^T_{i,1}, \ldots, \boldsymbol{\theta}^T_{i,N-1}]^T_{NL\times(Q+1)L}$ has the entry $\boldsymbol{\theta}_{i,n} = [diag\{\boldsymbol{\theta}_n, \boldsymbol{\theta}_n, \ldots, \boldsymbol{\theta}_n\}]_{L\times(Q+1)L}$, and $\boldsymbol{\rho}_i = [\boldsymbol{\rho}^T_{i,0}, \boldsymbol{\rho}^T_{i,1}, \ldots, \boldsymbol{\rho}^T_{i,L-1}]^T_{(Q+1)L\times 1}$.

Since $\boldsymbol{\rho}_i$. has $(Q + 1)L$ unknown parameters, $N_{group} \ge (Q + 1)L$ is necessary to guarantee the matrix $\boldsymbol{\beta}_i = \boldsymbol{\Lambda}_i\boldsymbol{\theta}_i$ to be of full column rank.

Thus, we estimate $\boldsymbol{\rho}_i$ as

$$\hat{\boldsymbol{\rho}}_i = \boldsymbol{\beta}_i^{\dagger}\mathbf{Y}_p = (\boldsymbol{\beta}_i^{H}\boldsymbol{\beta}_i)^{-1}\boldsymbol{\beta}_i^{H}\mathbf{Y}_p \tag{5}$$

where $(\cdot)^{\dagger}$ denotes the Moore-Penrose inverse matrix. Then, the path coefficient $h_{i,n,l}$ in (3) can be calculated based on $\hat{\boldsymbol{\rho}}_i$ and $H_{i,p,q}$ in (2) can be also obtained.

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 $N_p = (Q+1)(2d+1)L$ 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 $L \le 6$ can be assumed [5]. So the normalised spectral efficiency of TFT-OFDM is $\dfrac{N-(Q+1)(2d+1)L}{M+N}$. 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

Guard interval	CP-OFDM	TDS-OFDM	DPN-OFDM	TFT-OFDM
$M = N/4$	60.00%	80.00%	66.67%	79.30%
$M = N/8$	77.78%	88.89%	80.00%	87.52%
$M = N/16$	88.23%	94.12%	88.89%	92.59%

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 $N = 4096$, $M = 512$, $Q = 1$, $d = 1$ and $L = 6$ 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 based on either the training sequence or the pilot tone could be used [7]. It can be observed from Fig. 3 that the proposed TFT-OFDM solution obtains better bit error rate (BER) performance than the three conventional schemes. For example, when the BER is 0.1, compared with DPN-OFDM, CP-OFDM and TDS-OFDM, the SNR gain achieved by TFT-OFDM is about 1.0, 3.3 and 6.9 dB, respectively. The performance gain is caused by the improved channel tracking capability of the channel estimation and the corresponding iterative ICI cancellation, both of which in turn lead to the higher receiver complexity of TFT-OFDM than CP-OFDM and DPN-OFDM. However, TFT-OFDM still has lower complexity than TDS-OFDM owing to the avoidance of the conventional iterative IBI cancellation algorithm [4].

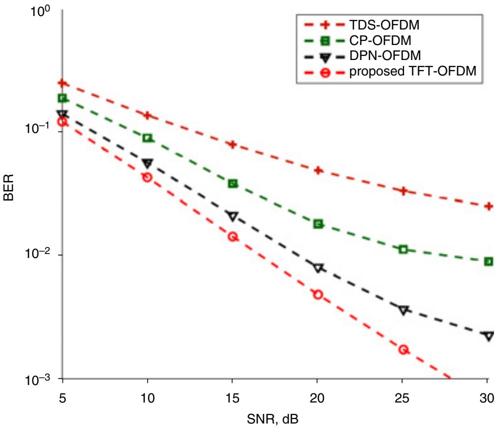

Fig. 3 *BER performance comparison between DPN-OFDM, CP-OFDM, TDS-OFDM and proposed TFT-OFDM schemes*

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 AQSIQ Project 200910244 and in part by the Tsinghua University Initiative Scientific Research Program 20091081280.

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: dll07@mails.tsinghua.edu.cn

References

1 Framing Structure, Channel Coding and Modulation for Digital Television Terrestrial Broadcasting System. Chinese National Standard, GB 20600-2006, Aug. 2006

2 Dai, L., Wang, Z., and Chen, S.: 'A novel uplink multiple access scheme based on TDS-FDMA', *IEEE Trans. Wirel. Commun.*, 2011, **10**, (3), pp. 757–761

3 Huemer, M., Hofbauer, C., and Huber, J.: 'Unique word prefix in SC/FDE and OFDM: a comparison'. Proc. IEEE Global Telecommunications Conf. (GLOBECOM'10), Miami, FL, USA, December 2010, pp. 1321–1326

4 Fu, J., Wang, J., Song, J., Pan, C., and Yang, Z.: 'A simplified equalisation method for dual PN-sequence padding TDS-OFDM systems', *IEEE Trans. Broadcast.*, 2008, **54**, (4), pp. 825–830

5 Tang, Z., Cannizzaro, R., Leus, G., and Banelli, P.: 'Pilot-assisted time-varying channel estimation for OFDM systems', *IEEE Trans. Signal Process.*, 2007, **15**, (5), pp. 2226–2238

6 Wang, X., Li, H., and Lin, H.: 'A new adaptive OFDM system with precoded cyclic prefix for dynamic cognitive radio communications', *IEEE J. Sel. Areas Commun.*, 2011, **29**, (2), pp. 431–442

7 Morelli, M., Kuo, C.C.J., and Pun, M.O.: 'Synchronization techniques for orthogonal frequency division multiple access (OFDMA): a tutorial review', *Proc. IEEE*, 2007, **95**, (7), pp. 1394–1427