This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2011 proceedings

Transmit Diversity Scheme for TDS-OFDM Systems with Reduced Complexity

Linglong Dai, Zhaocheng Wang, Jintao Wang and Jun Wang
Tsinghua National Laboratory for Information Science and Technology,
Electronics Engineering Department, Tsinghua University,
Beijing, 100084, P. R. China
E-mail: dll07@mails.tsinghua.edu.cn

***Abstract*—To reduce the complexity of existing transmit diversity solutions for time domain synchronous OFDM (TDS-OFDM), a simple transmit diversity scheme is proposed in this paper. The space shifted constant amplitude zero autocorrelation (CAZAC) sequence is used for time-domain channel estimation. Two types of flexible frame structures are investigated for cyclicity reconstruction of the received inverse discrete Fourier transform (IDFT) block. Regarding to channel estimation and cyclicity reconstruction, the complexity of the proposed scheme is only about 7% of the conventional solutions. With the penalty of small loss in spectral efficiency, the proposed scheme achieves better bit error rate performance over doubly selective channels, which is demonstrated by the simulation results.**

I. INTRODUCTION

In wireless communication systems, space diversity techniques are widely adopted to provide reliable transmission over severe fading channels [1]. Compared with receive diversity where every receiver has the increased hardware complexity, transmit diversity attracts more attention in broadcasting systems where thousands of users are served by one or several transmit towers. In the European second generation digital video terrestrial broadcasting (DVB-T2) standard, transmit diversity is used to provide high performance over wireless broadcasting channels [2].

Time domain synchronous OFDM (TDS-OFDM) is the key technology of the Chinese national digital television terrestrial broadcasting (DTTB) standard [3]. Several transmit diversity schemes for TDS-OFDM were proposed based on space-time block coding (STBC) [4] and space-time-frequency block coding (STFBC) [5], where ideal channel estimation was assumed. Frequency-domain channel estimation based on ST coded pseudorandom noise (PN) sequences was proposed in [6], where the hypothesis of static channels within two consecutive signal frames was required. Similarly, space-frequency (SF) coded training sequence (TS) was used for channel estimation in [7], where channel frequency responses (CFRs) over two adjacent subcarriers of the TS were assumed to be unchanged. On the other hand, the conventional schemes [6], [7] utilized the estimated channel impulse response (CIR) to remove the inter-symbol-interference (ISI) caused by TS and then reconstruct the cyclicity of the received inverse discrete Fourier transform (IDFT) block [8]. However, this method has poor reconstruction quality due to channel estimation inaccuracy, and requires high computational complexity.

In this paper, a simple transmit diversity scheme for TDS-OFDM systems with reduced complexity is proposed, where channel estimation and cyclicity reconstruction are achieved with low computational complexity. Specifically, the contributions of this paper are listed as below: 1) The space shifted constant amplitude zero autocorrelation (CAZAC) sequence is proposed for channel estimation with low complexity; 2) Two flexible frame structures are proposed to facilitate channel estimation and simple cyclicity reconstruction of the received IDFT block, where no prior channel state information is required; 3) The proposed transmit diversity scheme achieves better bit error rate (BER) performance than conventional solutions over doubly selective channels.

The remainder of this paper is organized as follows. Section II proposes the TDS-OFDM transmit diversity scheme. The corresponding receiver design is presented in Section III, together with the spectral efficiency and computational complexity analysis. Section IV shows the simulation results to evaluate the performance of the proposed scheme. This paper is concluded in Section V.

II. TRANSMITTER DESIGN FOR TRANSMIT DIVERSITY

In this section, the TS and flexible frame structure design are proposed, based on which the architecture of the TDS-OFDM transmit diversity scheme is outlined.

A. Space Shifted CAZAC Training Sequence

Instead of ST/SF coded TS adopted in conventional solutions [6], [7], CAZAC sequence [9] $\mathbf{c}_i$ with length of N_p can be used as TS for the ith transmit antenna

$$c_i(n) = \exp\left\{j\pi r n^2/N_p\right\}, \quad 0 \le n \le N_p - 1, \tag{1}$$

where r is relatively prime to N_p, and $r = N_p - 1$ is preferred to alleviate the impact of carrier frequency offset. CAZAC sequences have ideal autocorrelation property, which can be denoted by

$$R_c(k) = \sum_{n=0}^{N_p-1} c^*{}_i(n) c_i((n+k))_{N_p} = \begin{cases} N_p, & k = 0, \\ 0, & k \neq 0, \end{cases} \tag{2}$$

where $(\cdot)^*$ means complex conjugate, and $((\cdot))_{N_p}$ denotes the modulo-N_p operation.

To distinguish the individual wireless channel associated with each transmit antenna, CAZAC sequences $\mathbf{c}_i$ and $\mathbf{c}_{i+1}$

978-1-61284-233-2/11/$26.00 ©2011 IEEE

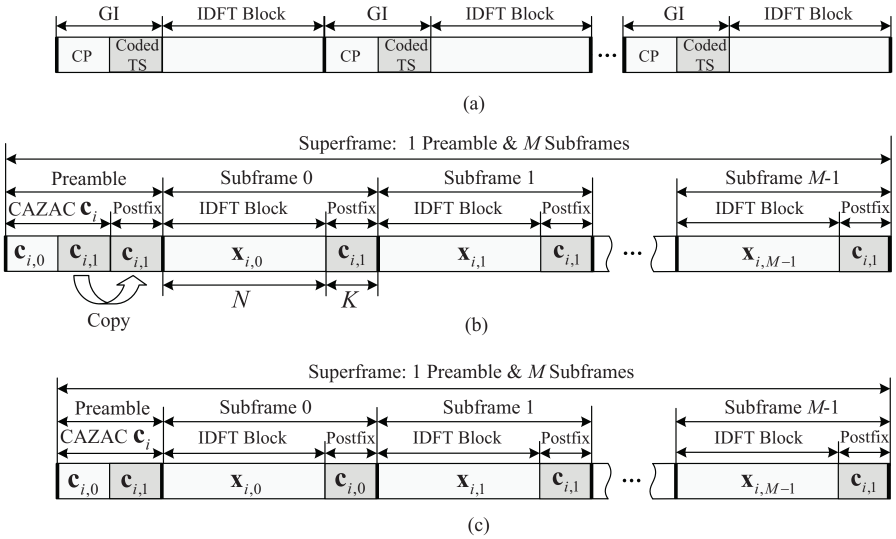

Fig. 1. Frame structures for TDS-OFDM transmit diversity schemes: (a) Conventional frame structure based on ST/SF coded TS with cyclic prefix (CP); (b) Proposed type 1: same postfix based frame structure (SPFS); (c) Proposed type 2: alternate postfix based frame structure (APFS).

for the adjacent ith and $(i+1)$th transmit antennas have a constant shift of K symbols, which can be defined by

$$c_{i+1}(n)=[c_i(K),c_i(K+1),...,c_i(N_p-1),c_i(0),...,c_i(K-1)]. \tag{3}$$

B. Frame Structure for Block Transmission

The frame structure of the conventional solutions [6], [7] based on ST/SF coded TS is shown in Fig. 1 (a). Similar to the dual PN-sequence padding scheme [3], The TS is protected by its cyclic prefix (CP) to absorb ISI from previous IDFT block. As shown in Fig. 1 (b) and (c) respectively, two types of flexible frame structures are proposed to enable TDS-OFDM transmit diversity scheme with low complexity. Without the loss of generality, the transmit antenna number N_T is assumed to be 2.

The basic block transmission unit for the proposed scheme is the superframe. Each superframe is composed of one CAZAC based preamble and M subframes. M could be adaptively adjusted according to the coherent time of the wireless channel. For example, lower Doppler spread leads to larger M, whereby higher spectral efficiency will be achieved, and vice versa. The mth subframe from the ith transmit antenna is consists of the IDFT block $\mathbf{x}_{i,m}$ with length of N and the postfix with length of K. Specifically, two types of frame structures are provided:

1) Type 1: *Same postfix based frame structure (SPFS).* As shown in Fig. 1 (b), the preamble is consisted of one CAZAC sequence $\mathbf{c}_i$ and its postfix $\mathbf{c}_{i.1}$, which is the second half of $\mathbf{c}_i$. In the following M subframes, every IDFT block is following by the same postfix $\mathbf{c}_{i.1}$. In this case, M could be an arbitrary number;
2) Type 2: *Alternate postfix based frame structure (APFS).* As shown in Fig. 1 (c), the preamble is just the CAZAC sequence, which can be divided into two halves, namely, the first half $\mathbf{c}_{i,0}$ and the second half $\mathbf{c}_{i,1}$. In the following M subframes, each subframe alternatively chooses $\mathbf{c}_{i,0}$ and $\mathbf{c}_{i,1}$ as its postfix. The postfix of the last subframe should be $\mathbf{c}_{i,1}$. Normally, $M = uN_T$ is required, where u is a positive integer.

SPFS and APFS can also be used for single-carrier block transmission.

C. Transmit Diversity Scheme for TDS-OFDM

Based on the proposed TS and frame structures, the transmit diversity scheme for TDS-OFDM system is shown in Fig. 2. Without the loss of generality, we focus on the system with two transmit antennas (denoted by Tx 1 and Tx 2, respectively) and one receive antenna (denoted by Rx).

At the transmitter, the space-frequency block coding (SFBC) similar to the Alamouti scheme [1] is applied to the input data. After IDFT block, the space shifted CAZAC sequences are used to construct the superframe signals as shown in Fig. 1 (b) or (c) for transmission via Tx 1 and Tx 2.

The multi-path CIR between the ith transmit antenna and the receive antenna in the mth subframe is denoted by $\mathbf{h}_{i,m}$, whose maximum delay spread L is assumed to be not larger than the postfix length in SPFS and APFS, i.e., $L \leq K$. The received IDFT block $\mathbf{y}_m$ in the mth subframe is given by

$$\mathbf{y}_m = \sum_{i=0}^{1} \mathbf{y}_{i,m} + \mathbf{w}_m = \sum_{i=0}^{1} \mathbf{x}_{i,m} * \mathbf{h}_{i,m} + \mathbf{w}_m, \tag{4}$$

where $\mathbf{y}_{i,m}$ denotes the response of the transmitted IDFT block $\mathbf{x}_{i,m}$ passing through the channel $\mathbf{h}_{i,m}$, $*$ is the linear convolution operator, and $\mathbf{w}_m$ is the additive white Gaussian noise (AWGN) with zero mean and the variance of σ^2.

At the receiver, the received CAZAC sequences and the corresponding local CAZAC sequences are used for channel estimation. The proposed frame structure is utilized to reconstruct the cyclicity of the received IDFT block with low complexity. The following space-frequency decoding can restore the transmitted data with diversity gain.

III. RECEIVER DESIGN FOR TRANSMIT DIVERSITY

Channel estimation and cyclicity reconstruction algorithms at the receiver are proposed in this section. The performance

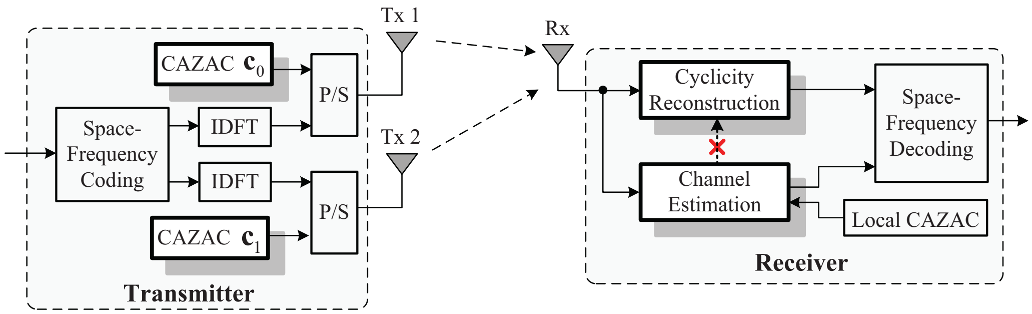

Fig. 2. Proposed transmit diversity scheme for TDS-OFDM system.

of the proposed transmit diversity scheme is also analyzed.

A. Channel Estimation

In both SPFS and APFS, the postfix of the last subframe belonging to the previous superframe naturally acts as the CP of the CAZAC sequence in the preamble. Assuming that channel is quasi-static during one superframe [10], the received CAZAC sequence $\mathbf{d}$ takes the form.

$$\mathbf{d} = \sum_{i=0}^{1} \mathbf{d}_i + \mathbf{w} = \sum_{i=0}^{1} \mathbf{c}_i \otimes \mathbf{h}_{i,m} + \mathbf{w}, \tag{5}$$

where $\otimes$ denotes the circular convolution, and $\mathbf{w}$ is the AWGN.

CIR estimate $\widehat{\mathbf{h}}^{(j)}$ in the jth superframe can be achieved by circular convolution between one local CAZAC sequence $\mathbf{c}_0$ with the received sequence $\mathbf{d}$ as below

$$\begin{aligned}\widehat{\mathbf{h}}^{(j)} &= \mathbf{c}_0 \otimes \mathbf{d} = \mathbf{c}_0 \otimes \left(\sum_{i=0}^{1} \mathbf{c}_i \otimes \mathbf{h}_{i,m} + \mathbf{w} \right) \\ &= N_p \left(\mathbf{h}_{0,m} + \mathbf{h}_{1,m} \delta[n-K] \right) + \mathbf{w}',\end{aligned} \tag{6}$$

where $\delta(n)$ denotes the Kronecker delta function, $\mathbf{w}' = \mathbf{c}_0 \otimes \mathbf{w}$ is the noise term whose statistical properties are the same as $\mathbf{w}$. Notice that the perfect autocorrelation of the CAZAC sequence denoted by (2) is used, e.g., $\mathbf{c}_0 \otimes \mathbf{c}_1 = N_p \delta(n-K)$. Intuitively, $\mathbf{h}_{1,m}$ is shifted by K symbols in the time dimension. If $L-1 \leq K$ and $N_p \geq K+L-1$, the CIR estimates $\{\widehat{\mathbf{h}}_{i,m}\}_{i=0}^{1}$ can be directly extracted from $\widehat{\mathbf{h}}^{(j)}$.

The expectation of the channel estimation error is

$$Mean = \frac{1}{N_p} E\left(\widehat{\mathbf{h}}_{i,m} - \mathbf{h}_{i,m} \right) = \frac{1}{N_p} E\left(\mathbf{c}_0 \otimes \mathbf{w} \right) = 0, \tag{7}$$

where $E(\cdot)$ is the expectation operator. The mean squared error (MSE) of the channel estimation error is

$$\begin{aligned} MSE &= \frac{1}{N_p} E\left\{ \left(\widehat{\mathbf{h}}_{i,m} - \mathbf{h}_{i,m} \right)^H \left(\widehat{\mathbf{h}}_{i,m} - \mathbf{h}_{i,m} \right) \right\} \\ &= \frac{1}{N_p} E\left\{ \left| \mathbf{c}_0 \otimes \mathbf{w}_m \right|^2 \right\} = \frac{\sigma^2}{P_s} = \frac{1}{\lambda}, \end{aligned} \tag{8}$$

where $(\cdot)^H$ denotes the Hermitian transpose, P_s is the transmitted signal power, and $\lambda \triangleq P_s/\sigma^2$ is the averaged signal-to-noise ratio (SNR).

To reduce the complexity, the time-domain circular correlation in (6) can also be implemented by inverse fast Fourier transform (IFFT) as below

$$\widehat{\mathbf{h}}^{(j)} = IFFT\left(\frac{FFT(\mathbf{d})}{FFT(\mathbf{c}_0)} \right), \tag{9}$$

where $FFT(\mathbf{c}_0)$ can be pre-stored at the receiver. Thus only one FFT module and one IFFT module are required.

When the channel is varying fast, the following low-complexity linear interpolation can be used

$$\widehat{\mathbf{h}}_m^{(j)} = \widehat{\mathbf{h}}^{(j)} + \frac{2m+1}{2M} \left(\widehat{\mathbf{h}}^{(j+1)} - \widehat{\mathbf{h}}^{(j)} \right), \quad 0 \leq m \leq M-1 \ , \tag{10}$$

where $\widehat{\mathbf{h}}_m^{(j)}$ is the interpolated CIR for the mth subframe. Then $\{\widehat{\mathbf{h}}_{i,m}\}_{i=0}^{1}$ can be extracted from $\widehat{\mathbf{h}}_m^{(j)}$ instead of $\widehat{\mathbf{h}}^{(j)}$.

B. Cyclicity Reconstruction

To reduce the complexity of the ISI removal based cyclcity reconstruction in conventional solutions [6], [7], the proposed frame structure can be used. Without the loss of generality, we take SPFS as an example, since the similar procedure could be applied to APFS.

The received mth subframe transmitted from the ith transmit antenna is denoted by $\mathbf{r}_{i,m} \triangleq \{r_{i,m}(n)\}_{n=0}^{N+K-1}$, and the received preamble is presented as $\mathbf{r}_{i,0} \triangleq \{r_{i,0}(n)\}_{n=0}^{N_p+K-1}$. The joint cyclicity reconstruction of the received IDFT block can be achieved by the following one step add-subtract operation

$$y'_m(n) = \begin{cases} \sum\limits_{i=0}^{1} \left[r_{i,m}(n) + r_{i,m}(n+N) - r_{i,0}(n+N_p) \right], & 0 \leq n \leq K-1, \\ \sum\limits_{i=0}^{1} r_{i,m}(n), & K \leq n \leq N-1. \end{cases} \tag{11}$$

If the wireless channel is quasi-static during one superframe, the "tails" caused by the postfixes in the preamble and the mth subframe due to multi-path effect could be assumed to be the same [3]. Therefore, (11) leads to

$$y'_m(n) = \sum_{i=0}^{1} y'_{i,m}(n), \quad 0 \leq n \leq N-1 \ , \tag{12}$$

where

$$y'_{i,m}(n) = \begin{cases} y_{i,m}(n+N) + y_{i,m}(n), & 0 \leq n < K-1, \\ y_{i,m}(n), & K \leq n \leq N-1. \end{cases} \tag{13}$$

The proposed joint cyclicity reconstruction method without ISI removal is applicable to any transmit antenna number scenarios with unchanged complexity.

C. Spectral Efficiency

The TS as well as the CP/postfix would decrease the spectral efficiency of TDS-OFDM systems. Table I compares the spectral efficiency of the conventional solutions with the proposed SPFS and APFS.

TABLE I
SPECTRAL EFFICIENCY COMPARISON.

	Spectral Efficiency
ST/SF coded TS [6], [7]	$N/(N+2K)$
Proposed SPFS	$N/(N+K+3K/M)$
Proposed APFS	$N/(N+K+2K/M)$

The spectral efficiency of the propose SPFS is higher than that of the conventional solutions when $M > 3$, while slightly lower than that of the APFS. However, due to its more flexible adaptation to channel variance and the fact that postfix in SPFS can be regarded as "unique word" for low-complexity frequency domain equalization [11], SPFS is preferred for the proposed transmit diversity scheme.

D. Computational Complexity

Regarding to channel estimation and cyclicity reconstruction, Table II compares the computational complexity between the conventional solutions and the proposed scheme. All the operations in Table II are based on N_p-symbol block.

TABLE II
COMPUTATIONAL COMPLEXITY COMPARISON.

	FFT/IFFT	Division	Convolution	Addition	Subtraction
ST coded [6]	$2+N_T$	1	$2N_T$	1	$2N_T$
SF coded [7]	$2+2N_T$	2	$2N_T$	1	$2N_T$
Proposed	2	1	0	1	1

Computational complexity can be evaluated in terms of multiplications. Taking the typical values $N_p = 256$, $N_T = 2$ for example, the complexity of the proposed scheme is only 7.20% of the ST coded PN based solution [6], and 6.71% of the SF coded TS based scheme [7].

IV. SIMULATION RESULTS

Simulations were carried out to investigate the performance of the proposed transmit diversity scheme for TDS-OFDM systems without channel coding and interleaving. The major system parameters are configured as below: 1) The signal bandwidth is 7.56 MHz with the central frequency of 770 MHz in the television ultra high frequency (UHF) band; 2) $N = 3780$, $K = 256$, $M = 2$; 3) QPSK modulation was adopted; 4) The symbol rate was 7.56 MHz, and the sub-carrier spacing was 2 kHz; 5) The DTTB test channel model Brazil E [12] with the maximum delay of 2 μs and the ITU defined channel model Vehicular B [13] with the maximum delay of 20 μs were used in the simulation. For Rayleigh fading channels, the maximum Doppler spread of 20 Hz and 100 Hz were considered with the corresponding receiver velocity of 28 km/h (slow time-varying) and 140 km/h (fast time-varying) in UHF band, respectively.

The proposed scheme was compared with other three types of systems: the single-antenna TDS-OFDM [3], the ST coded PN sequence [6] and the SF coded TS [7] based TDS-OFDM transmit diversity solutions, in terms of BER performance as a function of SNR.

Fig. 3 compares the BER performance between the proposed SPFS and APFS over Brazil E channel. It is clear that SPFS and APFS have very close performances, since they share the identical channel estimation and cyclicity reconstruction algorithms. Considering the discussion in Section III-C, it is recommended to adopt SPFS in the actual implementation. Therefore, only the proposed SPFS (denoted as "Proposed" for simplicity) is investigated in the following parts.

Fig. 4 shows the BER performance over the weakly frequency-selective Brazil E channel with the receiver velocity of 140 km/h. Compared with the single-antenna scheme, obvious BER improvement can be achieved. Fig. 4 indicates that the conventional solutions work well under the weakly frequency-selective and fast fading channels, while the proposed scheme has the best performance.

Fig. 5 and Fig. 6 present the BER performance over the deeply frequency-selective Vehicular B channel with the receiver velocity of 28 km/h and 140 km/h, respectively. The SF coded TS based transmit diversity solution [7] performs even worse than the single-antenna system without transmit diversity over the deeply frequency-selective channels. This is caused by the poor performance of channel estimation and cyclicity reconstruction of [7] when the CFRs over two adjacent subcarriers of the TS have large differences. It also shows that the proposed scheme has superior performance to the conventional solutions. Notice that $M = 2$ is selected for SPFS over fast fading channels, thus the spectral efficiency loss of 2.55% is expected compared with conventional solutions.

Compared with to the ST coded PN based solution [6], the proposed scheme can achieve more accurate CIR estimates over the preambles in the superframes, and channel variation

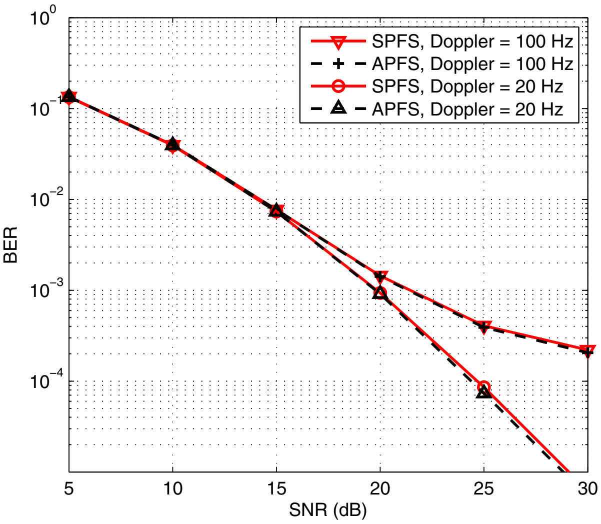

Fig. 3. BER performance comparison between the proposed SPFS and APFS over Brazil E channel.

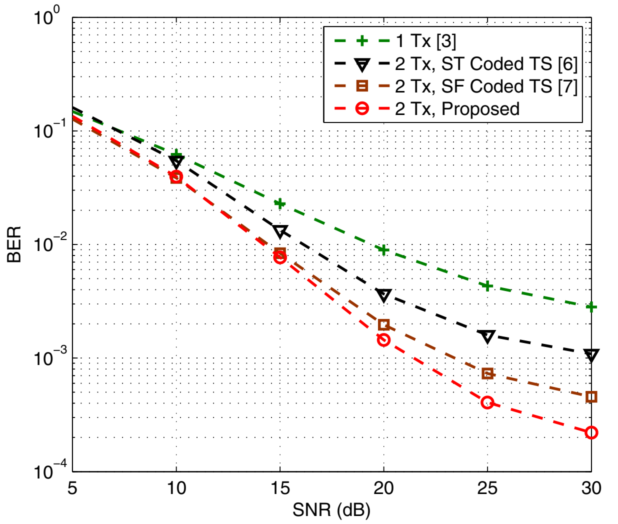

Fig. 4. BER performance comparison over Brazil E channel with the receiver velocity of 140 km/h.

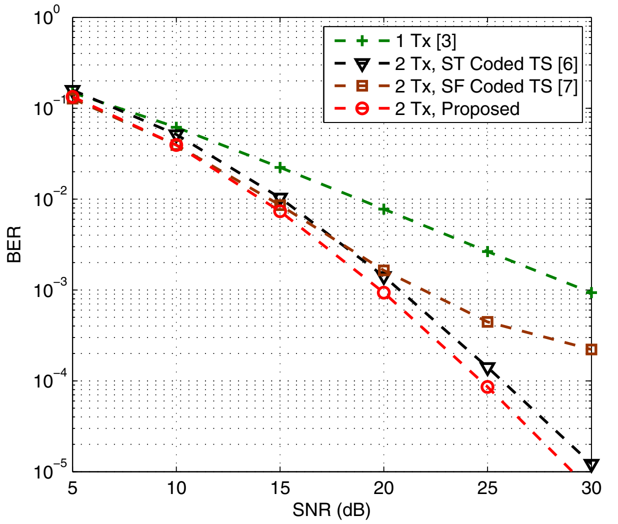

Fig. 5. BER performance comparison over Vehicular B channel with the receiver velocity of 28 km/h.

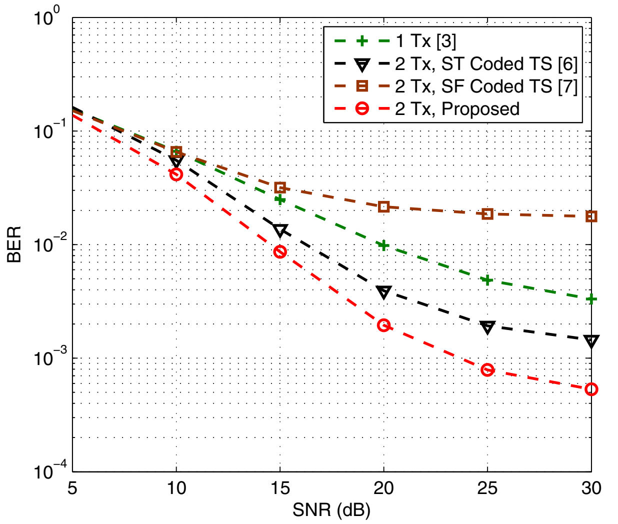

Fig. 6. BER performance comparison over Vehicular B channel with the receiver velocity of 140 km/h.

can be partly compensated by the interpolation as shown in (10). Therefore, more reliable channel estimation can be achieved. In addition, the performance of the proposed cyclicity reconstruction is only affected by the channel variation, while the conventional way in [6], [7] is influenced by both the channel fluctuation and channel estimation inaccuracy.

V. CONCLUSIONS

A simple transmit diversity scheme is proposed for TDS-OFDM systems with reduced complexity. The space shifted CAZAC sequence is proposed for channel estimation. Two types of flexible frame structures are proposed to reconstruct the cyclicity of the received IDFT block without prior channel information. Compared with the existing solutions, the proposed scheme achieves much lower complexity as well as better BER performance over doubly selective fading channels. The proposed scheme could be directly extended to support more antennas for both single-carrier and multi-carrier transmissions.

ACKNOWLEDGMENTS

This work was supported in part by Standardization Administration of the People's Republic of China (SAC) with AQSIQ Project 200910244 and in part by Tsinghua University Initiative Scientific Research Program.

REFERENCES

[1] M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[2] *Frame Structure, Channel Coding and Modulation for a Second Generation Digital Terrestrial Television Broadcasting System (DVB-T2)*. European Standard, ETSI EN 302 755, V1.1.1, Sep. 2009.

[3] J. Fu, J. Wang, J. Song, C. Pan, and Z. Yang, "A simplified equalization method for dual PN-sequence padding TDS-OFDM systems," *IEEE Trans. Broadcast.*, vol. 54, no. 4, pp. 825–830, Dec. 2008.

[4] J. Wang, J. Song, J. Wang, C. Pan, Z. Yang and L. Yang, "A general SFN structure with transmit diversity for TDS-OFDM system," *IEEE Trans. Broadcast.*, vol. 52, no. 2, pp. 245–251, Jan. 2006.

[5] J. Wang, Z. Yang, C. Pan, J. Song and L. Yang, "Design of space-time-frequency transmitter diversity scheme for TDS-OFDM system," *IEEE Trans. Consum. Electron.*, vol. 51, no. 3, pp. 759–764, Aug. 2005.

[6] F. Yang, K. Peng, J. Wang, J. Song, and Z. Yang, "Training sequence design for low complexity channel estimation in transmit diversity TDS-OFDM system," *IEICE Trans. Commun.*, vol. E92-B, no. 6, pp. 2308–2311, Jun. 2009.

[7] F. Yang, K. Peng, J. Wang, J. Song, and Z. Yang, "Channel estimation based on space-time-frequency coded training sequence for transmit diversity system," *IEICE Trans. Commun.*, vol. E92-B, no. 5, pp. 1901–1903, May 2009.

[8] B. Muquet, Z. Wang, and G. B. Giannakis, "Cylic prefixing or zero padding for wireless multicarrier transmissions?" *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 2136–2148, Dec. 2002.

[9] L. Boemer and M. Antweiler, "Perfect N-phase sequences and arrays," *IEEE J. Select. Areas Commun.*, vol. 10, no. 4, pp. 782–789, May 1992.

[10] X. Wang, M. J. Rahman, Y. Wu, B. Tian, K. Yi, and J.-Y. Chouinard, "A time slicing adaptive OFDM system for mobile multimedia communications," *IEEE Trans. Broadcast.*, vol. 56, no. 2, pp. 226–234, June 2010.

[11] L. Dai, Z. Wang, and C. Shen, "A novel uplink multiple access scheme based on TDS-FDMA," accepted by *IEEE Trans. Wireless Commun.*, Dec. 2010.

[12] *Guidelines and Techniques for the Evaluation of DTTB Systems*. ITU-R Document 6E/TEMP/131-E, 2003.

[13] *Guideline for Evaluation of Radio Transmission Technology for IMT-2000*. Recommendation ITU-R M.1225, 1997.