This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

# TDS-OFDM Transmit Diversity Based on Space-Time Shifted CAZAC Sequence

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***Abstract*—The existing transmit diversity schemes for time domain synchronous OFDM (TDS-OFDM) is only suitable either for fast time-varying but weakly frequency-selective channels, or strongly frequency-selective but slow fading channels. In this paper, the space-time shifted constant amplitude zero autocorrelation (CAZAC) sequence based TDS-OFDM transmit diversity scheme is proposed for doubly selective channels. The space-shifted CAZAC sequence is used for channel estimation, and the time-shifted sequence is utilized for the cyclicity reconstruction of the received inverse discrete Fourier transform (IDFT) block. Compared with the state-of-the-art solutions, the proposed scheme has lower complexity irrelative to the transmit antenna number, and it achieves better bit error rate (BER) performance under various multi-path fading channels.**

## I. INTRODUCTION

In wireless communications, the frequency-selectivity and time-selectivity of the channel are possibly encountered, i.e., the channel is doubly selective. Space diversity techniques are proven to be the effective and efficient solution to achieve high diversity gain and good performance without bandwidth or power penalty under wireless fading channels [1].

Compared with receiver diversity where hardware complexity is increased for every receiver, transmit diversity is more attractive, especially in broadcasting scenarios where one or several transmit towers are radiating signals to thousands of users. The recently announced standard for the second generation digital video terrestrial broadcasting (DVB-T2) also recommended transmit diversity to provide more reliable transmission under the similar propagation environments [2].

Time domain synchronous OFDM (TDS-OFDM) is the essential technology of the Chinese national digital television terrestrial broadcasting (DTTB) standard [3]. Instead of cyclic prefix (CP), the pseudo-noise (PN) sequence is padded before the inverse discrete Fourier transform (IDFT) block as the guard interval to avoid the inter-symbol-interference (ISI) and at the same time as the training sequence (TS) for synchronization and channel estimation (CE). Several transmit diversity schemes for TDS-OFDM were proposed based on space-time block coding (STBC) [4] or space-time-frequency block coding (STFBC) [5]. The system performances both in [4] and [5] were based on the perfect channel state information (CSI) and the ideal cyclicity reconstruction of the received IDFT block whose cyclicity was destroyed by the ISI. However, complex iterative algorithm [6] was required for CSI estimation and cyclicity reconstruction in single-antenna TDS-OFDM system, which become challenging for transmit diversity schemes due to the superposition of the signals from different transmit antennas. Inspired by the space-time (ST) coded TS [7], frequency-domain CE based on ST coded PN sequence was proposed in [8]. Similarly, space-frequency (SF) coded TS was presented for CE in [9].

Nevertheless, there are some shortcomings for those solutions. At first, the ST coded PN sequence based CE [8] required the hypothesis of static channels along consecutive two signal frames, which might be not the case in fast fading channels. The CE using SF coded TS assumed constant CSI over adjacent two pilots [9], which might be not true for deeply frequency-selective channels. Therefore, neither of them can be used in doubly selective channels. Secondly, they both utilized the estimated channel impulse response (CIR) to reconstruct the cyclicity of the received IDFT block, thus the reconstruction quality and consequently the system performance would be degraded by the CE errors, especially in doubly selective channels. Moreover, frequency-domain processing has higher complexity than the time-domain operation.

To solve those issues, a novel TDS-OFDM transmit diversity scheme based on the space-time shifted constant amplitude zero autocorrelation (CAZAC) sequence is proposed in this paper. The space-shifted CAZAC sequence is used for time-domain CE, and the time-shifted CAZAC sequence is utilized for cyclicity reconstruction of the received IDFT block, respectively. The main contributions of this paper are listed as below: 1) Unlike the SF coded TS based CE which is applicable to fast time-varying but weakly frequency-selective channels, or the ST coded TS based CE which is suitable for strongly frequency-selective but slow fading channels, the CE method in this paper works well under both deeply frequency-selective and rapid fading channels; 2) The cyclicity reconstruction of the received IDFT block is realized without any CIR information, so the impact of the CE errors is avoided and system performance is improved; 3) The receiver complexity is reduced.

The rest of this paper is organized as follows. Section II illustrates the system model of the TDS-OFDM transmit diversity scheme using the space-time shifted CAZAC sequence. The corresponding receiver algorithms are presented in Section III, together with the computational complexity analysis. Section IV shows the simulation results to verify the feasibility and performance of the proposed scheme. We then conclude this paper in Section V.

## II. System Model

In this section, the novel frame structure using the space-time shifted CAZAC sequence is firstly presented, based on which the system model of the TDS-OFDM transmit diversity scheme is then outlined.

### A. Space-Time Shifted CAZAC Sequence

Instead of the SF/ST coded PN sequence, the space-time shifted CAZAC sequence is used for the TDS-OFDM transmit diversity system. Fig. 1 shows the frame structure for the proposed scheme.

The signal for the $i$th transmit antenna in the $m$th frame is composed of the IDFT block $\mathbf{x}_{i,m}$ with length $N$ and the TS $\mathbf{p}_{i,m}$ with length $N_g$. The TS consists of the space-time shifted CAZAC sequence $\mathbf{c}_{i,m}$ with length $N_c$ and its $K$-symbol cyclic extension ($N_g = N_c + K$)

$$p_{i,m}(n) = \begin{cases} c_{i,m}(n-K+N_c) & 0 \le n \le K-1 \\ c_{i,m}(n-K) & K \le n \le N_g - 1 \end{cases}. \quad (1)$$

The CAZAC sequence can be selected according to [10]

$$c_{i,m}(n) = e^{j\pi r n^2/N_c} \quad 0 \le n \le N_c - 1, \quad (2)$$

where $r$ is relatively prime to $N_c$. The CAZAC sequence has perfect autocorrelation denoted by

$$R_c(k) = \sum_{n=0}^{N_c-1} c^*{}_{i,m}(n) c_{i,m}((n-k))_{N_c} = \begin{cases} N_c & k=0 \\ 0 & k \neq 0 \end{cases}, \quad (3)$$

where $(\cdot)^*$ means complex conjugate, and $((\cdot))_{N_c}$ is the modulo-$N_c$ operator.

The space-time shifted CAZAC sequence is presented as

$$\begin{cases} \mathbf{c}_{i+1,m} = \mathbf{c}_{i,m}^{\Xi_K} \\ \mathbf{c}_{i,m+1} = \mathbf{c}_{i,m}^{\Xi_K} \end{cases}, \quad (4)$$

where $(\cdot)^{\Xi_K}$ denotes the $K$-symbol cyclic shift operation. In the space dimension, the CAZAC sequences for adjacent two antennas have a constant $K$-symbol cyclic shift to facilitate CE at the receiver. In the time dimension, the CAZAC sequences for consecutive two signal frames similarly hold a constant $K$-symbol cyclic shift to simplify the cyclicity reconstruction at the receiver.

### B. Transmit Diversity Scheme for TDS-OFDM

Based on the physical layer of TDS-OFDM system specified in the Chinese DTTB standard [3], the transmit diversity scheme for TDS-OFDM using the space-time shifted CAZAC sequence is shown in Fig. 2. For simplicity, we focus on the system with $N_T = 2$ transmit antennas and $N_R = 1$ receive antenna.

At the transmitter, the space-frequency block coding (SFBC) [11] is applied to the constellation mapped input data before the IDFT is applied. Then the space-time shifted

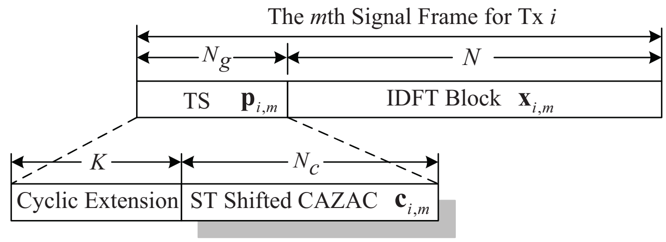


Fig. 1. Frame structure of the proposed transmit diversity scheme.

CAZAC sequences are padded between adjacent IDFT blocks in the time domain to form the signal frames shown in Fig. 1 for transmission via Tx 1 and Tx 2 antennas.

The multi-path CIR between the $i$th transmit antenna and the receive antenna in the $m$th frame $\mathbf{h}_{i,m}$ is modeled as an $L$-order finite impulse response (FIR) filter. The maximum delay spread of the channel $L$ is assumed to be not larger than the length of the cyclic extension in the TS, i.e., $L \le K$. The received IDFT block in the $m$th frame is given by

$$\mathbf{r}_m = \sum_{i=1}^{2} \mathbf{y}_{i,m} + \mathbf{w}_m = \sum_{i=1}^{2} \mathbf{x}_{i,m} * \mathbf{h}_{i,m} + \mathbf{w}_m, \quad (5)$$

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 $\sigma^2$.

At the receiver, the CE using the space-shifted CAZAC sequence works well under doubly selective channels. The cyclicity reconstruction of the received IDFT block is realized by the time-shifted CAZAC sequence without any CIR information. The following process including DFT and space-frequency decoding can restore the transmitted signal with the diversity gain.

## III. Receiver Design for Transit Diversity

The receiver algorithms based on the space-time shifted CAZAC sequence are addressed in this section. The corresponding complexity is also analyzed in the sequel.

### A. Channel Estimation under Doubly Selective Channels

Protected by the cyclic extension, the received space-shifted CAZAC sequence is immune to the ISI caused by the multi-path dispersion. Therefore, the actually received CAZAC sequence $\mathbf{g}_m$ at the receiver inherits the cyclicity property and takes the form

$$\mathbf{g}_m = \sum_{i=1}^{2} \mathbf{c}_{i,m} \otimes \mathbf{h}_{i,m} + \mathbf{w}_m, \quad (6)$$

where $\otimes$ denotes the circular convolution.

Circular convolution between one local CAZAC sequence $\mathbf{c}_{1,m}$ with the received signal $\mathbf{g}_m$ will generate the orthogonally separable CIR estimates of $\mathbf{h}_{i,m}$ ($i = 1, 2$) as follows

$$\begin{aligned} \mathbf{c}_{1,m} \otimes \mathbf{g}_m &= \mathbf{c}_{1,m} \otimes \left( \sum_{i=1}^{2} \mathbf{c}_{i,m} \otimes \mathbf{h}_{i,m} + \mathbf{w}_m \right) \\ &= N_c \left( \mathbf{h}_{1,m} + \mathbf{h}_{2,m} \delta[n-K] \right) + \mathbf{w}'_m, \end{aligned} \quad (7)$$

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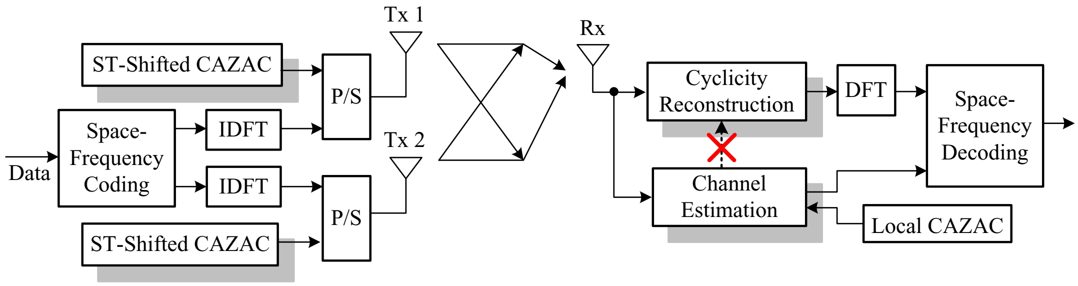


Fig. 2. TDS-OFDM transmit diversity system based on the space-time shifted CAZAC sequence.

where $\mathbf{w}'_m = \mathbf{c}_{1,m} \otimes \mathbf{w}_m$ is the noise term, and the perfect autocorrelation of the CAZAC sequence denoted by (3) is utilized, e.g., $\mathbf{c}_{1,m} \otimes \mathbf{c}_{2,m} = N_c \delta(n-K)$. Intuitively, $\mathbf{h}_{2,m}$ is shifted by $K$ symbols to the right. If $L-1 \leq K$ and $N_c \geq K+L-1$, the CIR estimates $\widehat{\mathbf{h}}_{1,m}$ and $\widehat{\mathbf{h}}_{2,m}$ can be directly extracted from (7).

Unlike the ST or SF coded TS, the space-time shifted CAZAC sequence also holds the ideal autocorrelation after cyclic shifting, so the correlation based synchronization can be directly applied in every signal frame. In addition, synchronization can be simultaneously achieved with the circular convolution based time-domain CE [12].

### *B. Cyclicity Reconstruction*

The time-shifted CAZAC sequence is used for cyclicity reconstruction with low complexity. From (1) and (4), the TS in the $(m+1)$th frame can be expressed as

$$p_{i,m+1}(n) = \begin{cases} c_{i,m}(n) & 0 \leq n \leq N_c - 1 \\ c_{i,m}(n-N_c) & N_c \leq n \leq N_g - 1 \end{cases} . \quad (8)$$

From (1) and (8), it is clear that the IDFT block $\mathbf{x}_{i,m}$ is enclosed by two identical CAZAC sequences $\mathbf{c}_{i,m}$. Those three parts can be viewed as the "virtual frame" with length $N+2N_c$. The corresponding received signal is shown by $\{r_{i,m}(n)\}_{n=0}^{N+2N_c-1}$ in Fig. 3 (a), where the shadows mean the "tails" due to the multi-path effect. The following one step add-subtract operation will accomplish the cyclicity reconstruction of the received IDFT block

$$y'_{total,m}(n) = \begin{cases} \sum_{i=1}^{2} r_{i,m}(n+N_c) + r_{i,m}(n+N_c+N) - r_{i,m}(n) & 0 \leq n \leq K-1 \\ \sum_{i=1}^{2} r_{i,m}(n+N_c) & K \leq n \leq N-1 \end{cases} , \quad (9)$$

where $\{r_{i,m}(n)\}_{n=0}^{K-1}$ is the last $K$ symbols of the received TS in the $m$th frame, $\{r_{i,m}(n+N_c)\}_{n=0}^{N-1}$ is the received IDFT block in the $m$th frame, and $\{r_{i,m}(n+N_c+N)\}_{n=0}^{K-1}$ is the first $K$ symbols of the received TS in the $(m+1)$th frame, as shown in Fig. 3(a).

If the wireless channel is quasi-static during one signal frame, the "tails" shown by the shadows with the same form in Fig. 3 (a) will be assumed to be identical. So we have

$$y'_{total,m}(n) = \sum_{i=1}^{2} y'_{i,m}(n) \quad 0 \leq n \leq N-1 , \quad (10)$$

where

$$y'_{i,m}(n) = \begin{cases} y_{i,m}(n+N) + y_{i,m}(n) & 0 \leq n < K-1 \\ y_{i,m}(n) & K \leq n \leq N-1 \end{cases} . \quad (11)$$

The procedure to generate $\mathbf{y}'_{i,m} = \{y'_{i,m}(n)\}_{n=0}^{N-1}$ (e.g., $i=1$) in (11) and the consequent process to obtain $\mathbf{y}'_{total,m}$ in (9) are also illustrated by Fig. 3(b) and Fig. 3(c), respectively. Clearly, $\mathbf{y}'_{i,m}$ $(i=1,2)$ is the cyclicity reconstructed IDFT block for Tx $i$, and $\mathbf{y}'_{total,m}$ also holds the cyclicity property. Therefore, cyclicity reconstruction of the received IDFT block is achieved via the simple one step add-subtract operation in (9). Note that this method still works if the channel is not quasi-static during one signal frame, which will be verified by

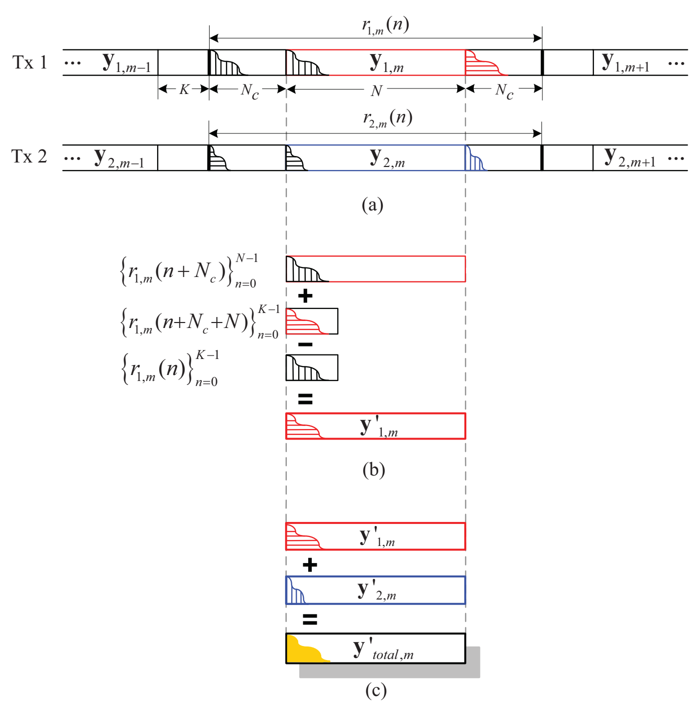


Fig. 3. Cyclicity reconstruction for TDS-OFDM based transmit diversity system in the $m$th frame: (a) Received signal from Tx 1 and Tx 2; (b) Cyclicity reconstruction of the IDFT block for Tx 1; (c) Joint cyclicity reconstruction for Tx 1 and Tx 2.

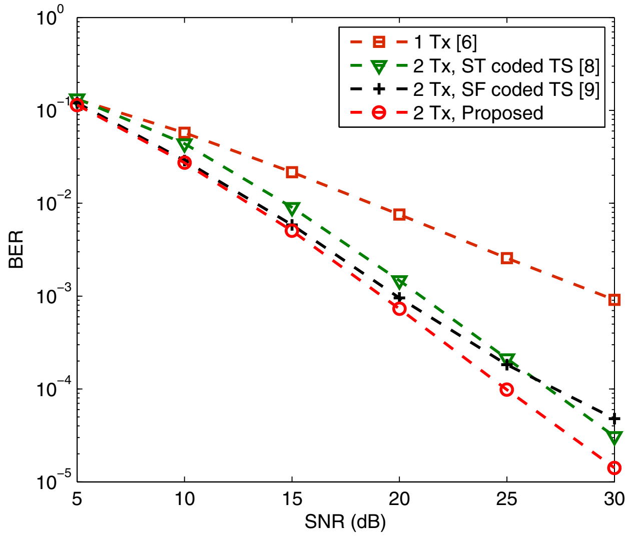


Fig. 4. BER performance comparison under the weakly frequency-selective Vehicular A channel with the receiver velocity of 28 km/h.

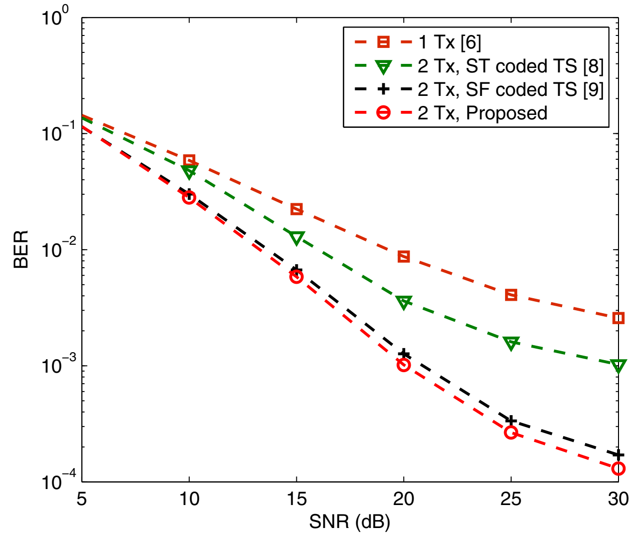


Fig. 5. BER performance comparison under the weakly frequency-selective Vehicular A channel with the receiver velocity of 140 km/h.

computer simulations in Section IV.

### *C. Computational Complexity*

Regarding to CE and cyclicity reconstruction, Table I compares the computational complexity between the proposed scheme and the SF/ST coded TS based systems [8] [9]. All the operations in Table I are based on the signal block with length $N_c$. It is clear that much lower complexity is achieved by the proposed scheme.

TABLE I
COMPUTATIONAL COMPLEXITY COMPARISON.

| | FFT/IFFT | Division | Convolution | Addition | Subtraction |
|---|---|---|---|---|---|
| SF coded [8] | $2+2N_T$ | 2 | $2N_T$ | 1 | $2N_T$ |
| ST coded [9] | $2+N_T$ | 1 | $2N_T$ | 1 | $2N_T$ |
| Proposed | 0 | 0 | 1 | 1 | 1 |

Both the SF/ST coded TS based systems require FFT/IFFT for frequency-domain CFR estimation and then derived the CIR for ISI removal and cyclicity reconstruction. The proposed system only needs one time-domain circular convolution to acquire the CIR, and cyclicity reconstruction is accomplished by the one step add-subtract operation without any CIR information. Note that the corresponding complexity is irrelative to the transmit antenna number $N_T$, thus more complexity will be reduced when $N_T$ is large.

## IV. SIMULATION RESULTS AND DISCUSSIONS

Simulations are carried out to validate the feasibility and the performance of the proposed transmit diversity scheme for TDS-OFDM system without channel coding and interleaving. The major system parameters are configured as below: 1) The signal bandwidth is 8 MHz at the central frequency of 770 MHz in the television ultra high frequency (UHF) band; 2) $N = 3780$, $N_c = 256$, $K = 128$; 3) QPSK modulation is selected; 4) The symbol rate is 7.56 MSPS, and the subcarrier spacing is 2 kHz; 5) The ITU-R defined channel model Vehicular A [13] and the DTTB test model Brazil D [14] are used. The Vehicular A channel with short delay spread is weakly frequency-selective, while the Brazil D channel with a long echo emulating the single frequency network (SFN) scenario, has strong frequency-selectivity. For Rayleigh fading channels, we use the maximum Doppler spread of 20 Hz and 100 Hz with the corresponding receiver velocity of 28 km/h (slow time-varying) and 140 km/h (fast time-varying) at 770 MHz, respectively.

Fig. 4 and Fig. 5 show the bit error rate (BER) performance under the weakly frequency-selective Vehicular A channel with the receiver velocity of 28 km/h and 140 km/h, respectively. Compared with the single-antenna scheme, obvious BER improvement can be achieved by transmit diversity. Fig. 4 indicates that both the SF and ST based methods work well under the weakly frequency-selective and slow fading channels, while the proposed scheme has the best performance. Fig. 5 shows that the performance of both the SF and ST based schemes deteriorate in the fast fading channel, especially for the ST based method. It also shows that the proposed scheme still has the best performance.

Fig. 6 and Fig. 7 present the BER performance under the strongly frequency-selective Brazil D channel with the receiver velocity of 28 km/h and 140 km/h, respectively. The SF based CE can not work under the deeply frequency-selective channels like Brazil D. Under the slow fading channel (e.g., the receiver velocity is 28 km/h in Fig. 6), the proposed scheme outperforms the ST based method with the SNR gain by about 1 dB for the target BER of $1 \times 10^{-3}$, while the SNR improvement gap is enlarged to be about 10 dB under the doubly selective fading channel (e.g., the receiver velocity is 140 km/h in Fig. 7).

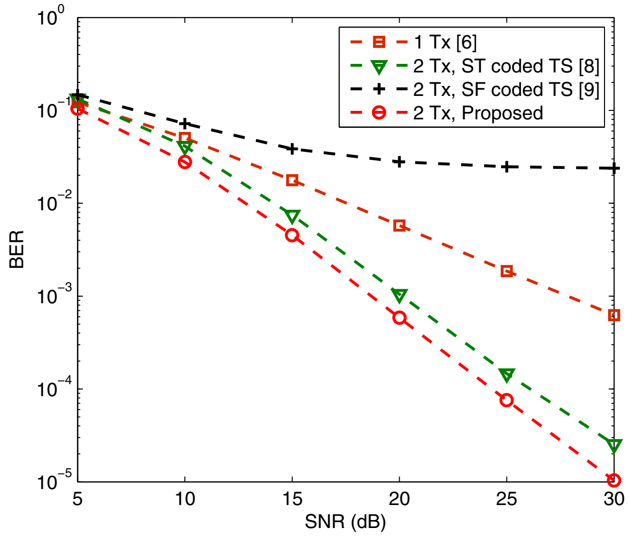


Fig. 6. BER performance comparison under the strongly frequency-selective Brazil D channel with the receiver velocity of 28 km/h.

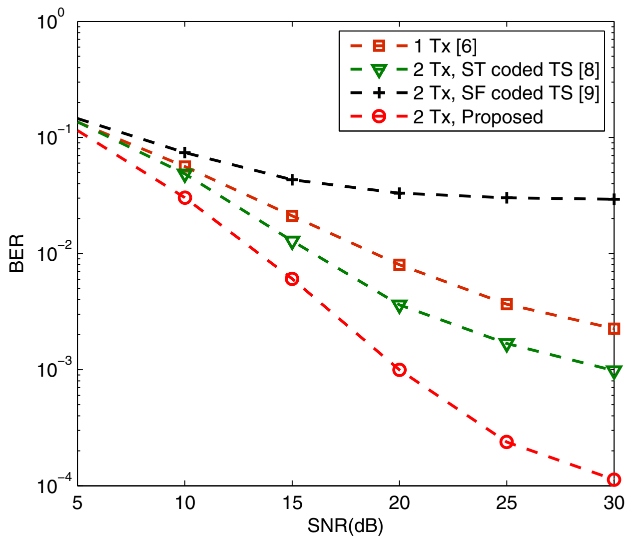


Fig. 7. BER performance comparison under the strongly frequency-selective Brazil D channel with the receiver velocity of 140 km/h.

The reason for the superior BER performance of the proposed TDS-OFDM based transmit diversity scheme under four types of fading channels (i.e., the combination of the strongly/weakly frequency-selective and fast/slow time-varying channel) lies in two aspects. Firstly, due to the specific frame structure with the time-shifted CAZAC sequence, the simple yet efficient cyclicity reconstruction is accomplished without any CIR information, which avoids the impact of the CE errors and consequently improves the system performance. Secondly and more importantly, the space-shifted CAZAC sequence based CE does not rely on the assumption of constant CFR along adjacent two frequency-domain pilots, or depend on the hypothesis of static channels during consecutive two signal frames. Therefore, the CFR over every pilot can be updated each frame, leading to the high robustness of the proposed scheme to both the strongly frequency-selective and fast time-varying channels.

## V. Conclusion

A novel TDS-OFDM transmit diversity system with low complexity based on the space-time shifted CAZAC sequence is proposed in this paper. Compared with the existing solutions, the proposed scheme provides better system performance under both strongly frequency-selective and fast time-varying wireless fading channels. The concept of the space-time shifted TS could be directly extended to support more antennas for both single-carrier and multi-carrier transmissions in the uplink or downlink. Due to its low complexity and good performance under doubly selective channels, the proposed scheme could be adopted as a potential transmit diversity solution to the Chinese next generation broadcasting standard.

## Acknowledgments

This work was supported in part by Tsinghua University Initiative Scientific Research Program (No. 20091081280) and in part by a grant from the Ph.D. Programs Foundation of Ministry of Education of China (No. 20090002120026).

## References

[1] S. 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, Sept. 2009.

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

[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, June 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. Consumer Electron.*, vol. 51, no. 3, pp. 759–764, Aug. 2005.

[6] J. Wang, Z. Yang, C. Pan, and J. Song, "Iterative padding subtraction of the PN sequence for the TDS-OFDM over broadcast channels," *IEEE Trans. Consumer Electron.*, vol. 51, no. 11, pp. 1148–1152, Nov. 2005.

[7] Y. Gong and K. B. Letaief, "Low complexity channel estimation for space-time wideband OFDM systems," *IEEE Trans. Wireless Commun.*, vol. 2, no. 5, pp. 876–882, Sept. 2003.

[8] 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, June 2009.

[9] F. Yang, K. Peng, J. Wang, 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.

[10] 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.

[11] K. F. Lee and D. B. Williams, "Space-frequency transmitter diversity technique for OFDM systems," in *Proc. IEEE 43th Global Telecommunications Conf. (GLOBECOM'00)*, San Francisco, CA, Nov. 2000, pp. 1473–1477.

[12] L. Dai, J. Fu, J. Wang, and J. Song, "A multi-user uplink TDS-OFDM system based on dual PN sequence padding," *IEEE Trans. Consumer Electron.*, vol. 55, no. 3, pp. 1098–1106, Aug. 2009.

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

[14] *Digital Television Systems-Brazilian Tests-Final Report*. SET/ABERT ANATEL SP, May 2000.