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A Novel TDS-FDMA Scheme for Multi-User Uplink Scenarios

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***Abstract*—Time domain synchronous OFDM (TDS-OFDM) with higher spectral efficiency than cyclic prefix OFDM (CP-OFDM) was originally proposed for downlink broadcasting transmission. To support multi-user uplink scenarios, this paper proposes a novel multiple access scheme called time domain synchronous frequency division multiple access (TDS-FDMA), wherein an uniform frame structure and its corresponding receiver algorithms are presented for both single-carrier and multi-carrier signal transmission. Compared with typical OFDMA systems, TDS-FDMA has higher spectral efficiency. The multi-user TDS-FDMA receiver has lower complexity than the conventional single-user TDS-OFDM receiver, and it can achieve better bit error rate (BER) performance under the slow to medium time-varying channels.**

I. Introduction

Orthogonal frequency division multiple access (OFDMA) has been widely adopted as the multiple access solution in many wireless communication standards [1]. OFDMA was firstly proposed for cable TV (CATV) networks [2] and then used in the uplink of the interaction channel for digital terrestrial television (DVB-RCT) [3]. IEEE 802.16e adopted OFDMA both in the uplink and downlink [4]. Recently, OFDMA attracts vast research attentions from both academia and industry [5].

As the essential technology of the Chinese national digital television terrestrial broadcasting (DTTB) standard [6], time domain synchronous OFDM (TDS-OFDM) outperforms cyclic prefix OFDM (CP-OFDM) in spectral efficiency at the cost of higher complexity [7]. Instead of padding CP before the inverse discrete Fourier transform (IDFT) block, TDS-OFDM adopts the pseudo-random noise (PN) sequence as the guard interval (GI), which is also used for synchronization and channel estimation (CE) [7] [8]. Therefore, the cyclicity of the received IDFT block is destroyed due to the inter-symbol-interference (ISI) between the PN sequence and the IDFT block. The iterative interference cancellation algorithm is proposed to remove the ISI [9]. Some improved methods have been proposed either to increase the accuracy [10] or to reduce the complexity [11]. However, those iterative methods [9]–[11] have high complexity and unsatisfactory performance due to the fact that CE and interference cancellation are mutually conditional, i.e., perfect CE is needed for ideal interference cancellation, while perfect interference cancellation is required for ideal CE.

Until now, TDS-OFDM has been used only in the downlink broadcasting transmission. When TDS-OFDM is applied to the uplink multiple access scenarios, if multiple users are supported, the PN sequences from multiple users would cause the superposed interferences to the IDFT blocks, and the IDFT blocks from multiple users would also introduce the mixed interferences to the PN sequences. Such superposed interferences have to be removed before restoring the orthogonality among multiple users. Unfortunately, the previously mentioned iterative methods [9]–[11] can not be directly applied, since the superposed interferences caused by multiple users are difficult to be eliminated.

To solve this problem, based on the principle of TDS-OFDM and frequency division multiple access (FDMA), we propose a novel uplink multiple access scheme called time domain synchronous FDMA (TDS-FDMA) in this paper. The main contribution of the proposed TDS-FDMA system is the new frame structure. The key idea of the new frame structure lies in two aspects: 1) The specially designed frame structure makes the CE and interference cancellation in the proposed TDS-FDMA system no longer mutually conditional, so the conventional iterative methods can be avoided, leading to the low complexity of the joint cyclictiy reconstruction of the received IDFT blocks; 2) The preamble in the frame structure enables timing synchronization and joint channel estimation for all users to be realized by an one-step circular convolution.

The remainder of this paper is organized as follows. Section II illustrates the overall architecture of the proposed TDS-FDMA system based on the novel frame structure. The corresponding TDS-FDMA receiver algorithms are presented in Section III, together with the analysis of spectral efficiency and computational complexity. Section IV shows the simulation results to verify the feasibility and performance of the proposed system. We then conclude this paper in Section V.

II. Architecture of the TDS-FDMA System

In this section, we firstly present the novel frame structure of the uplink multi-user TDS-FDMA system, based on which the overall architecture is then outlined.

A. Frame Structure

Fig. 1 shows the frame structure for the mth user of the proposed TDS-FDMA system. Every user adopts the same

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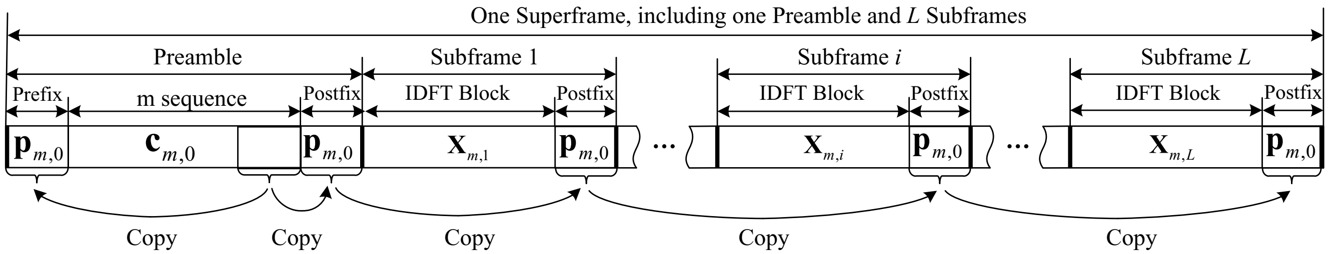

Fig. 1. Frame Structure of the TDS-FDMA System.

frame structure in the proposed TDS-FDMA system. The basic block transmission unit is the superframe, which is composed of one preamble and L subframes.

The N_g-point preamble in the superframe consists of three parts: the user-specific N_p-point m-sequence $\mathbf{c}_{m,0}$, the K-point prefix and the K-point postfix $\mathbf{p}_{m,0}$. Unlike the frame header of the TDS-OFDM system where the cyclic prefix and cyclic postfix with different lengths and distinct contents are used, the prefix and the postfix in the TDS-FDMA system are exactly the same, both of which are the last K symbols of the m-sequence $\mathbf{c}_{m,0}$. Therefore, $N_g = N_p + 2K$.

For the multiple users locating at different places, the user-specific m-sequences between neighboring users hold a constant circular shift L_s, which can be presented as

$$\mathbf{c}_{m+1,0} = \mathbf{c}_{m,0}^{\Xi_{L_s}}, \quad (1)$$

where $\mathbf{c}_{m,0}$ and $\mathbf{c}_{m+1,0}$ are the user-specific m-sequences for the mth user and the $(m+1)$th user, respectively. $\mathbf{c}^{\Xi_{L_s}}$ means the L_s-symbol circular shift of the vector $\mathbf{c}$.

The N_f-point subframe $\mathbf{s}_{m,i}$ consists of the N-point IDFT block $\mathbf{x}_{m,i}$ and the K-point postfix $\mathbf{p}_{m,i}$, and $N_f = N + K$. The postfix $\mathbf{p}_{m,i}$ is not relative to the IDFT block $\mathbf{x}_{m,i}$ in every subframe, but identical with the prefix and postfix in the preamble. That is

$$\mathbf{p}_{m,i} = \mathbf{p}_{m,0} \quad 1 \le i \le L. \quad (2)$$

The number of subframes L could be adaptively adjusted according to the coherent time of the wireless channel.

B. System Architecture

At the transmitter part, M users simultaneously transmit their signals to a central base station. The generation of the IDFT block for the mth user in the ith subframe is as follows: the input frequency-domain data $\mathbf{D}_{m,i} = \{D_{m,i}(k)\}_{k=0}^{L_m-1}$ ($N = \sum_{m=1}^{M} L_m$) are mapped onto the sub-carrier set Γ_m assigned to the mth user by the carrier assignment scheme (CAS) unit, and an N-dimensional vector $\mathbf{X}_{m,i} = \{X_{m,i}(k)\}_{k=0}^{N-1}$ is generated with entries

$$X_{m,i}(k) = \begin{cases} D_{m,i}(k) & k \in \Gamma_m \\ 0 & k \notin \Gamma_m \end{cases} \quad 1 \le m \le M \ . \quad (3)$$

The sub-carrier sets $\{\Gamma_m\}_{m=1}^{M}$ must be mutually exclusive to guarantee the orthogonality, i.e., $\Gamma_i \cap \Gamma_j = \emptyset$ if $i \neq j$. The time-domain IDFT block $\mathbf{x}_{m,i} = \{x_{m,i}(n)\}_{n=0}^{N-1}$ is then obtained by applying IDFT operation to the frequency-domain data $\mathbf{X}_{m,i}$. After padding the postfix $\mathbf{p}_{m,0}$ after $\mathbf{x}_{m,i}$ to construct L subframes, the user-specific preamble is inserted at the beginning of each superframe. The superframe is transmitted over a user-specific multi-path channel. The channel impulse response (CIR) is modeled as an l_m order FIR filter $\mathbf{h}_{m,i} = \{h_{m,i}(l)\}_{l=0}^{l_m-1}$, and l_m is the maximum delay spread of the user-specific CIR $\mathbf{h}_{m,i}$.

At the receiver part, firstly, as presented in Section III.A, jointly cyclicity reconstructed signal $\mathbf{y}'_{total,i}$ of the received IDFT block for all M users is achieved via an one-step add-subtract operation. The orthogonal separation of the multiple access signals can be then achieved in the frequency domain to obtain the user-specific frequency-domain signal $\mathbf{Y}'_{m,i} = \{Y'_{m,i}(k)\}_{k=0}^{N-1}$ for the mth user, whose entries take the form

$$Y'_{m,i}(k) = H_{m,i}(k) \cdot X_{m,i}(k) + W_{m,i}(k) \quad 0 \le k \le N-1. \quad (4)$$

where $\mathbf{H}_{m,i} = \{H_{m,i}(k)\}_{k=0}^{N-1}$ is the N-point DFT of the user-specific CIR $\mathbf{h}_{m,i}$, $W_{m,i}(k)$ is the complex-valued additive white Gaussian noise (AWGN) in the frequency domain.

Secondly, as derived in Section III.B, joint channel estimation can be realized by the circular convolution between one local m-sequence and the received m-sequence, whereby the equivalent "total" CIR $\widehat{\mathbf{h}}_{total,i}$ is generated, which is the orderly concatenation of all the user-specific CIRs $\{\mathbf{h}_{m,i}\}_{m=1}^{M}$. Therefore, orthogonal separation of the CIRs for multiple users can be achieved in the time domain to get the user-specific CE result $\widehat{\mathbf{h}}_{m,i}$ for the mth user.

After the user-specific signal $\mathbf{Y}'_{m,i}$ and CE result $\widehat{\mathbf{H}}_{m,i}$ in the frequency domain for each user are obtained, the classical one-tap frequency domain equalization (FDE) can be carried out either by the zero-forcing (ZF) approach or alternatively the minimum mean square error (MMSE) equalizer with relatively good performance and high complexity [12]

$$\widehat{\mathbf{D}}_{m,i} = \frac{\widehat{\mathbf{H}}_{m,i}^{*} \cdot \mathbf{Y}'_{m,i}}{\left|\widehat{\mathbf{H}}_{m,i}\right|^2 + 1/\gamma} \quad 1 \le m \le M, \ 1 \le i \le L, \quad (5)$$

where γ is the signal-to-noise ratio (SNR), $(\cdot)^*$ means complex conjugation, and $\widehat{\mathbf{D}}_{m,i}$ is the estimate of the frequency-domain transmitted data $\mathbf{D}_{m,i}$.

It should be pointed out that the IDFT block in the proposed frame structure could be either the OFDMA type of multi-carrier (MC) signal or the single carrier FDMA (SC-FDMA) type of single-carrier (SC) signal [13], and the corresponding receiver algorithms based on the frame structure is applicable to both cases. Therefore, an uniform frame structure and the corresponding system architecture are provided in this paper for both the MC and SC uplink transmission.

III. TDS-FDMA Receiver Design

In this section, the TDS-FDMA receiver design issues based on the new frame structure are addressed, together with the analysis of the spectral efficiency and the computational complexity.

A. Joint Cyclicity Reconstruction

At the base station, the received time-domain signal is the linear superposition of all M user-specific signals passing through different wireless channels. The following one-step add-subtraction operation between the received IDFT block, the postfix in the subframe and the postfix in the preamble would produce the jointly cyclicity reconstructed N-point signal $\mathbf{y}'_{total,i}$ of the IDFT block

$$y'_{total,i}(n) = \begin{cases} \sum_{m=1}^{M} r_{m,i}(n)+r_{m,i}(n+N)-r_{m,0}(n+N_p+K) & 0\le n\le K-1 \\ \sum_{m=1}^{M} r_{m,i}(n) & K\le n\le N-1 \end{cases} . \quad (6)$$

where $\{r_{m,i}(n)\}_{n=0}^{N-1}$ is the received IDFT block in the ith subframe, $\{r_{m,i}(n+N)\}_{n=0}^{K-1}$ is the received postfix in the ith subframe, and $\{r_{m,0}(n+N_p+K)\}_{n=0}^{K-1}$ is the received postfix in the preamble, as shown in Fig. 2(a). $\mathbf{y}_{m,i} = \mathbf{x}_{m,i} \odot \mathbf{h}_{m,i} = \{y_{m,i}(n)\}_{n=0}^{N+K-1}$ in Fig. 2(a) denotes the response of the IDFT block $\mathbf{x}_{m,i}$, where $\odot$ means the linear convolution.

Assuming the wireless channel during one superframe is quasi-static, i.e., $\{\mathbf{h}_{m,i}\}_{i=1}^{L} = \mathbf{h}_{m,0}$, the postfix in the preamble and the postfix in the ith subframe would introduce the same "tail" due to multi-path dispersion, as shown by the shadows with the same form in Fig. 2 (a). Therefore, we have

$$y'_{total,i}(n) = \sum_{m=1}^{M} y'_{m,i}(n) \quad 0 \le n \le N-1 , \quad (7)$$

where

$$y'_{m,i}(n) = \begin{cases} y_{m,i}(n+N)+y_{m,i}(n) & 0\le n\le K-1 \\ y_{m,i}(n) & K\le n\le N-1 \end{cases} . \quad (8)$$

The procedure to generate $\mathbf{y}'_{m,i} = \left\{y'_{m,i}(n)\right\}_{n=0}^{N-1}$ in (8) and the consequent process to obtain $\mathbf{y}'_{total,i}$ in (6) and (7) can be illustrated by Fig. 2(b) and Fig. 2(c), respectively. Similar to the IDFT block after removing the CP in typical CP based OFDM/OFDMA systems, $\mathbf{y}'_{m,i}$ is the cyclicity reconstructed signal of the ith received IDFT block for the mth user, and joint cyclictiy reconstruction for all M users is achieved via the one-step add-subtraction operation in (6) to obtain $\mathbf{y}'_{total,i}$.

Denoting $\mathbf{Y}'_{total,i} = \left\{Y'_{total,i}(k)\right\}_{k=0}^{N-1}$ as the N-point DFT of $\mathbf{y}'_{total,i}$, then the user-specific frequency-domain signal $\mathbf{Y}'_{m,i} = \left\{Y'_{m,i}(k)\right\}_{k=0}^{N-1}$ for channel equalization in (5) for the mth user could be selected out of $\mathbf{Y}'_{total,i}$, according to the same CAS at the transmitter defined by (3)

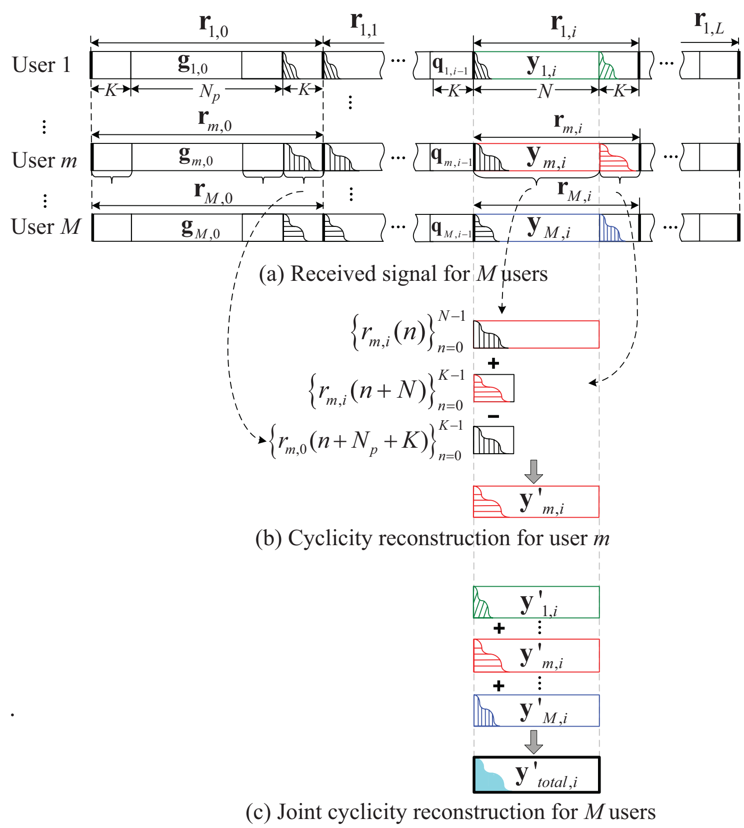

Fig. 2. Joint cyclictiy reconstruction of the received IDFT block for all M users in the TDS-FDMA system.

$$Y'_{m,i}(k) = \begin{cases} Y'_{total,i}(k) & k \in \Gamma_m \\ 0 & k \notin \Gamma_m \end{cases} \quad 1 \le m \le M . \quad (9)$$

Because the sub-carrier sets for all users are mutually orthogonal and the cyclicity property of the IDFT block has been reconstructed, the linearly superposed signal in the time domain is orthogonally separated in the frequency domain.

B. Joint Channel Estimation

This part addresses the second design element of the TDS-FDMA receiver: channel estimation for the uplink multiple users for coherent detection. The actual received m-sequence $\mathbf{g}_m = \{r_{total,0}(n)\}_{n=K}^{K+N_p-1}$ at the TDS-FDMA receiver intrinsically inherits the cyclicity property due to the cyclic prefix in the preamble and takes the form

$$\mathbf{g}_m = \sum_{m=1}^{M} \mathbf{c}_{m,0} \otimes \mathbf{h}_{m,i}, \quad (10)$$

where $\otimes$ denotes the circular convolution.

Using a local m-sequence $\mathbf{c}_{1,0}$ to do circular convolution with the received m-sequence $\mathbf{g}_m$, we can get the equivalent "total" CIR $\widehat{\mathbf{h}}_{total,i}$, which is the sequential concatenation of all the user-specific CIRs $\{\mathbf{h}_{m,i}\}_{m=1}^{M}$

$$\begin{aligned}\widehat{\mathbf{h}}_{total,i} &= \mathbf{g}_m \otimes \mathbf{c}_{1,0} = \left(\sum_{m=1}^{M} \mathbf{c}_{m,0} \otimes \mathbf{h}_{m,i}\right) \otimes \mathbf{c}_{1,0} \\ &= N_p \cdot \sum_{m=1}^{M} \mathbf{h}_{m,i} \cdot \delta[n-(m-1)\cdot L_s].\end{aligned} \tag{11}$$

In (11), we have utilized the good autocorrelation property of the m-sequence and the circular phase shift feature of the m-sequences in the preamble denoted by (1), whereby the cross-correlation between $\mathbf{c}_{j,0}$ and $\mathbf{c}_{k,0}$ ($\mathbf{c}_{j,0} = \mathbf{c}_{k,0}^{\Xi_{(j-k)L_s}}$) could be written as

$$\mathbf{c}_{j,0} \otimes \mathbf{c}_{k,0} = N_p \cdot \delta[n-(j-k)\cdot L_s] \quad 1 \leq j,k \leq M \ . \tag{12}$$

Intuitively, equation (11) shows that the user-specific CIR $\mathbf{h}_{m,i}$ is shifted by $(m-1)L_s$ symbols. If $l_{\max} = \max_m \{l_m\}_{m=1}^{M} \leq L_s$ and $ML_s \leq N_p$, the shifted CIRs $\{\mathbf{h}_{m,i}\}_{m=1}^{M}$ are orthogonally separable in the time domain.

In addition, the uplink timing synchronization can be also realized by circular convolution in (11), whereby the timing errors for all users are less than half of the sampling period under multi-path channels [14].

C. Spectral Efficiency

Table I compares the spectral efficiency of the proposed TDS-FDMA system and the DVB-RCT system in the 2K mode ($N = 2048$) with three types of burst structure (BS) [3]. Because DVB-RCT can update the channel state information (CSI) every 6 OFDMA signal frames with the pilot insertion scheme specified in [3], we select $L = 5$ to guarantee the equivalent CSI updating speed for TDS-FDMA.

TABLE I
SPECTRAL EFFICIENCY OF DVR-RCT AND TDS-FDMA.

GI Length	DVR-RCT BS1	DVR-RCT BS2	DVR-RCT BS3	TDS-FDMA
K = N/16	75.29%	77.00%	77.89%	84.22%
K = N/8	71.11%	72.73%	73.56%	78.44%

It is clear that the increase of the spectral efficiency by about $5\%\sim9\%$ can be achieved for the TDS-FDMA system. The reason for the increased spectral efficiency is that, the frequency-domain pilots and the time-domain CP result in the decrease of the spectral efficiency for typical OFDMA systems like DVB-RCT, while the preamble and the postfix only in the time domain lead to the spectral efficiency loss for the proposed TDS-FDMA system.

D. Computational Complexity

Regarding to cyclicity reconstruction and channel estimation, Table II compares the computational complexity of the conventional single-user TDS-OFDM receiver and the proposed multi-user TDS-FDMA receiver. To be consistent with the TDS-OFDM system [6], the parameters are configured as $N = 3780$, $N_p = 255$. J is the iteration number in Table II. Note that the 255-point circular convolution for the joint channel estimation in (11) is implemented by 512-point FFT/IFFT for higher computing efficiency.

TABLE II
COMPLEXITY COMPARISON BETWEEN TDS-OFDM AND TDS-FDMA.

Operation	Wang [9]	Tang [10]	Yang [11]	Proposed
512-point FFT/IFFT	0	0	0	3
1024-point FFT/IFFT	$2J$	$2(J+1)$	$3(J+1)$	0
3780-point FFT/IFFT	$2J$	$5(J+1)$	1	1
8192-point FFT/IFFT	$2J$	0	0	0

We can see from this table that the computational complexity of the proposed multi-user TDS-FDMA receiver is only 6.1% of the traditional single-user TDS-OFDM receiver adopting Wang's method [9] with $J = 3$, and 6.0% of the Tang's method [10], 35.1% of the Yang's method [11], respectively.

IV. SIMULATION RESULTS AND DISCUSSIONS

Simulations are carried out to verify the feasibility and the performance of the proposed TDS-FDMA system without channel coding and interleaving. The major system parameters are configured as below: 1) Multi-carrier signal with the bandwidth of 8 MHz in the ultra high frequency (UHF) band at 770 MHz; 2) $M = 4$, $N = 3780$, $N_p = 255$, $K = 64$, $L = 5$; 3) The modulation schemes were chosen to be QPSK and 16QAM; 4) The multi-path channel model, Vehicular-A as defined by ITU [15], was used. 4) The maximum Doppler spread f_d of 5 Hz, 20 Hz, and 50 Hz with the corresponding velocity of 7 km/h, 28 km/h, and 70 km/h in the UHF band, are used respectively.

Fig. 3 and Fig. 4 compare the bit error rate (BER) performance of the multi-user TDS-FDMA system with that of the single-user TDS-OFDM system over the Vehicular-A Rayleigh fading channel, for the QPSK and 16QAM schemes, respectively. In TDS-FDMA, the BER is averaged among active users. The multi-user TDS-FDMA system achieved a superior BER performance over the single-user TDS-OFDM system. For example, in the QPSK case, an SNR improvement of about 1.8 dB was achieved by the multi-user TDS-FDMA for the target BER of 10^{-3} when $f_d = 5$ Hz, while the SNR gain was increased to be about 5 dB when $f_d = 20$ Hz. However, the SNR gain achieved by the TDS-FDMA over the TDS-OFDM became negligible for the high Doppler spread of $f_d = 50$ Hz. Therefore, we can conclude that higher BER performance could be achieved for the proposed multi-user TDS-FDMA system under slow to medium time-varying channels.

The reasons for the performance improvement both under static and fading channels lie in two aspects. Firstly, the received m-sequence in the new frame structure for joint CE is immune to the interferences caused by the IDFT block, leading to more accurate CE in mobile environments. Secondly, the joint cyclicity reconstruction does not need any CSI at all, and

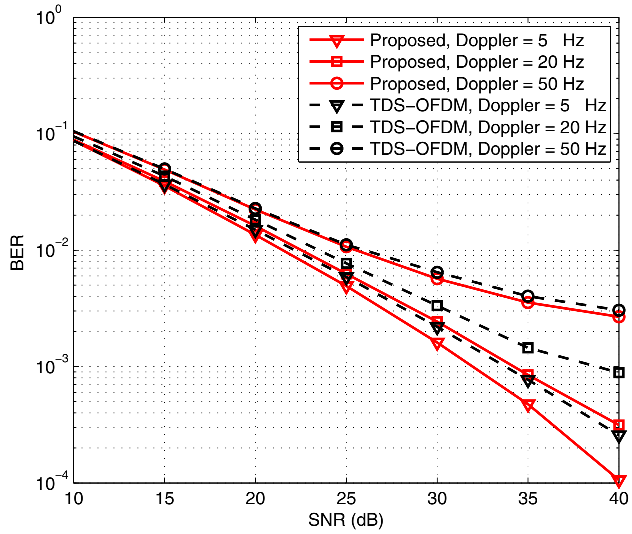

Fig. 3. BER performance comparison of the proposed multi-user TDS-FDMA system and the conventional single-user TDS-OFDM system over the Vehicular-A Rayleigh fading channel with the QPSK modulation scheme.

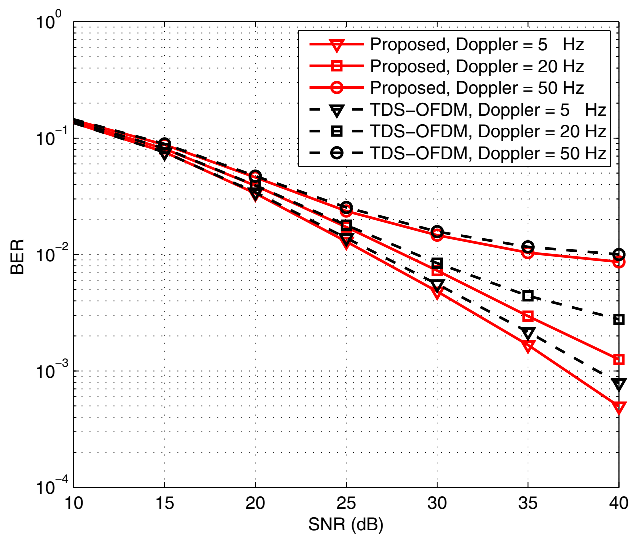

Fig. 4. BER performance comparison of the proposed multi-user TDS-FDMA system and the conventional single-user TDS-OFDM system over the Vehicular-A Rayleigh fading channel with the 16QAM modulation scheme

consequently, it avoids the conventional iterative interference cancellation between the PN sequence and the IDFT block. Thus it avoids the accumulated errors due to the imperfect CE and residual ISI during the iteration process in high-speed mobile environments. However, when the channel is varying too fast, e.g.,f_d is up to 50 Hz, the preamble based CSI updating speed becomes relatively low which counteracts the performance gain explained above, so no obvious performance gain can be achieved. This problem can be solved by decreasing L at the cost of spectral efficiency, which is unavoidable for reliable transmission in high-speed environments.

V. Conclusion

The major difficulty of eliminating the superposed interferences from multiple users when TDS-OFDM is extended to multi-user uplink scenarios is resolved by the proposed TDS-FDMA scheme in this paper. It can achieve higher spectral efficiency by about $5\%\sim9\%$ than typical OFDMA systems like DVB-RCT. Based on the novel frame structure, the conventional complex iterative interference cancellation methods are avoided, and the corresponding receiver algorithms can be realized with lower complexity for both the MC and SC uplink transmission. TDS-FDMA also achieves better BER performance than the signal-user TDS-OFDM scheme. Due to its low complexity and good performance compared with conventional TDS-OFDM system, TDS-FDMA scheme could be adopted as a potential uplink solution to the Chinese next generation broadcasting standard.

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