Joint Channel Estimation and Time-Frequency Synchronization for Uplink TDS-OFDMA Systems

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Abstract — *As one of the key technologies of the Chinese national digital television terrestrial broadcasting (DTTB) standard, time domain synchronous OFDM (TDS-OFDM) is used in the downlink broadcasting transmission scenarios. Based on TDS-OFDM, the uplink multiple access scheme called TDS-OFDMA has been recently proposed. The TDS-OFDMA system assumes perfect timing and frequency synchronization, both of which are difficult to be achieved in the uplink transmission where each user's signal is characterized by the user-specific timing and frequency errors. By utilizing the time-domain constant amplitude zero autocorrelation (CAZAC) training sequence and the "time-space two-dimensional frame structure", this paper proposes a joint channel estimation and time-frequency synchronization scheme for TDS-OFDMA. The channel estimation has the minimum mean square error (MSE), the timing synchronization is accurate and the frequency synchronization error can reach the Cramer-Rao lower bound (CRLB). The joint algorithm only relies on the time-domain circular correlation, thus low complexity is achieved. Simulation results demonstrate the performance of the proposed joint method under both additive white Gaussian noise (AWGN) and multi-path channels.* [1]

Index Terms — TDS-OFDMA, Channel Estimation, Timing Synchronization, Frequency Synchronization, Low Complexity.

I. INTRODUCTION

Due to the robustness to multi-path transmission and flexible frequency granularity, orthogonal frequency division multiple access (OFDMA) has been widely adopted as the multiple access technology in many wireless communication standards like DVB-RCT [1], the long term evolution (LTE) [2], and IEEE 802.16e [3].

In most OFDM systems, cyclic prefix (CP) is used as the guard interval to avoid the inter-symbol-interference (ISI). As the essential technology of the Chinese national digital television terrestrial broadcasting (DTTB) standard [4], time domain synchronous OFDM (TDS-OFDM) adopts the pseudo-noise (PN) sequence instead of CP as the guard interval, and the PN sequence is also used for synchronization and channel estimation [5-6]. TDS-OFDM is mainly used in the downlink broadcasting, and OFDMA is a promising solution to provide TDS-OFDM with the multiple access capability. Based on that, a novel TDS-OFDM based multiple access system called TDS-OFDMA was proposed in [7], whereby the "time-space two-dimensional frame structure" could solve the problem of the superposed interferences caused by different users. However, this scheme works well under the assumption of perfect timing and frequency synchronization, which is not true in actual applications, especially in the uplink multiple access scenarios whereby each user is characterized by the different timing and frequency errors.

Synchronization for the uplink OFDMA systems has inspired hot research interest recently [8]–[13]. For typical OFDMA systems, CP based timing synchronization is not accurate enough, so the concept of quasi-synchronous model is adopted, whereby a relatively long CP encompassing both the physical channel impulse response (CIR) duration and the two-way propagation delays of each user is required to combat the user-specific timing errors [8]. In this way, the timing errors are incorporated as part of the channel responses and thus can be compensated by the channel equalizer, leading to the fact that timing recovery is unnecessary and the base station only has to estimate the carrier frequency offsets (CFO). Clearly, the cost of the quasi-synchronous model is a certain loss of the transmission efficiency due to the extended CP length, especially when the propagation delays of some users are relatively large. To keep the spectral efficiency loss to a tolerable level, the length of the CP must be retained within a reasonable range, resulting in an upper limit to the maximum allowed propagation delay and consequently the maximum distance between the users and the base station. More accurate timing estimation can be achieved by some extra training sequences with specially designed patterns such as the [+A +A −A −A] type of training block proposed by Minn [9] and the [+A −A +A +A] type of reference block proposed by Shi [10], but extra training blocks would also result in the decrease of the transmission efficiency.

For frequency synchronization, the CFO estimators that can be only used in the subband carrier assignment scheme (CAS) type or the interleaved CAS type of OFDMA systems were proposed in [12] and [13], respectively. The space-alternating projection expectation maximization (SAGE) based iterative frequency synchronization can be used for the generalized CAS type of OFDMA systems, but the complexity is relatively high.

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Another issue of OFDMA systems is that channel estimation is usually achieved by orthogonal frequency-domain pilots, which are not available for the TDS-OFDMA system. So other resources have to be resorted for channel estimation. Besides, channel estimation and time-frequency synchronization are often separately discussed and achieved both in the TDS-OFDM system and typical OFDMA systems, thus high complexity is required.

To solve those problems, this paper proposes a joint channel estimation and time-frequency synchronization scheme for the TDS-OFDMA system. The main contributions of this paper are as follows: 1) The channel estimation with the optimal mean square error (MSE) is achieved by simultaneously utilizing the constant amplitude zero autocorrelation (CAZAC) training sequence and the "time-space two-dimensional frame structure" of the TDS-OFDMA system; 2) Timing and frequency synchronization of all the active users could be simultaneously achieved for any type of CAS. 3) Channel estimation and time-frequency synchronization are all based on the time-domain circular correlation, so they can be jointly implemented with low complexity.

The remainder of this paper is organized as follows. Section II illustrates the frame structure and the corresponding system model of the TDS-OFDMA scheme. The joint algorithm for channel estimation and time-frequency synchronization is presented in Section III, together with the computational complexity analysis. Section IV shows the simulation results to illustrate the feasibility and performance of the proposed joint scheme. We then conclude this paper in Section V.

Notation: We use the bold font to denote matrices and column vectors; $\mathbf{I}_N$ is the $N\times N$ identity matrix; * means the linear convolution; $\otimes$ is the circular convolution; $(\cdot)^*$, $(\cdot)^T$, $(\cdot)^H$ and $(\cdot)_N$ denote the complex conjugate, transpose, conjugate transpose, and modulo-N, respectively; $E\{\cdot\}$ is the expectation operator; $tr\{\cdot\}$ is the trace operator; $\hat{x}$ means the estimate of x; $\arg\{x\}$ denotes the angular of x; $\delta(n)$ is the Kronecker delta function.

II. TDS-OFDMA System Model

For the TDS-OFDMA system with M active users, Fig. 1 shows the "time-space two-dimensional frame structure" for the mth user in the ith frame. The signal frame of length N_f consists of a length-N inverse discrete Fourier transform (IDFT) block $\mathbf{x}_{m,i}$ and a length-N_g guard interval, which is composed of a length-N_p training sequence $\mathbf{p}_{m,i}$ and the corresponding length-N_t cyclic extension. The PN sequence is selected as the training sequence. The training sequences in the time and space dimensions are defined as

$$\begin{cases}\mathbf{p}_{m,i+1} = \mathbf{p}_{m,i}^{\Xi_{N_t}} \\ \mathbf{p}_{m+1,i} = \mathbf{p}_{m,i}^{\Xi_{N_s}}\end{cases}, \tag{1}$$

where $(\cdot)^{\Xi_K}$ is the K-symbol circular shift operator, N_t and N_s are the circular shifts in the time and space dimensions, respectively. $N_t \le N_s$ and $MN_s \le N_p$ are assumed.

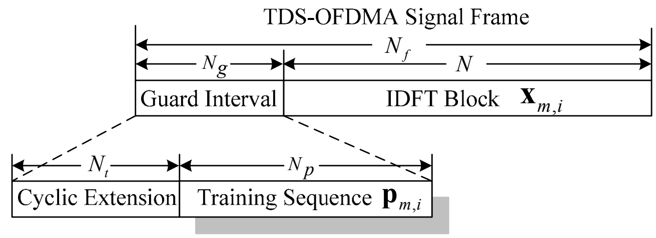

Fig. 1. The *i*th TDS-OFDMA signal frame for the *m*th user.

Based on the "time-space two-dimensional frame structure", Fig. 2 shows the TDS-FDMA baseband system model where M users are simultaneously transmitting their signals to a central base station [7].

At the transmitter part, the CAS unit assigns the constellation mapped user-specific data in the frequency domain onto the mutual orthogonal subcarrier sets before IDFT is applied. Then the cyclically extended training sequences defined by (1) are padded between adjacent IDFT blocks to form the TDS-OFDMA signal frames for transmission.

The multi-path CIR between the mth user and the base station in the ith frame $\mathbf{h}_{m,i} = \left[h_{m,i}(0), h_{m,i}(1), ..., h_{m,i}(L_m - 1)\right]^T$ is modeled as an L_m-order finite impulse response (FIR) filter. The maximum delay of the channel L_m is assumed to be smaller than the cyclic extension length, i.e., $L_m \le N_t$. The received IDFT block $\mathbf{r}_i$ in the ith frame can be expressed as

$$\mathbf{r}_i = \sum_{m=1}^{M} \mathbf{x}_{m,i} * \mathbf{h}_{m,i} + \mathbf{w}_i, \tag{2}$$

where the vector $\mathbf{w}_i$ is the additive white Gaussian noise (AWGN) with zero mean and the variance of σ^2.

At the receiver, the joint cyclicity reconstruction of the received IDFT block is realized by "time-space two-dimensional frame structure" without any prior CIR information, as presented in [7]. The specially designed training sequences can be also used for joint channel estimation and time-frequency synchronization.

III. Joint Scheme for Channel Estimation and Timing-Frequency Synchronization

Using the "time-space two-dimensional frame structure" of the TDS-OFDMA system, the joint scheme for channel estimation and time-frequency synchronization is addressed, which can be achieved by the low-complexity circular correlation in the time domain. The computational complexity of the proposed method will be also analyzed.

A. Channel Estimation

Protected by the cyclic extension, the received training sequence $\mathbf{q}_i$ in the ith TDS-OFDMA signal frame inherits the

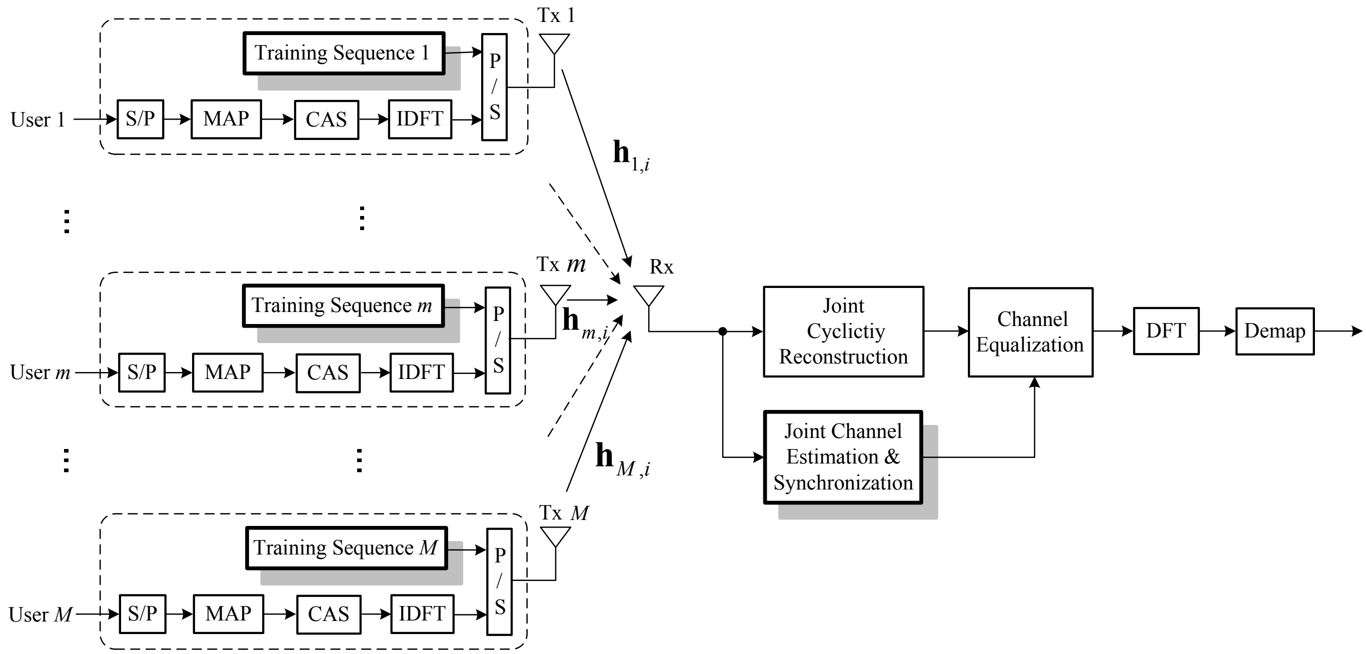

Fig. 2. TDS-OFDMA baseband system model.

cyclicity property and takes the form

$$\begin{aligned}\mathbf{q}_i &= \sum_{m=1}^{M} \mathbf{p}_{m,i} \otimes \mathbf{h}_{m,i} + \mathbf{v}_i = \sum_{m=1}^{M} \tilde{\mathbf{P}}_{m,i}\mathbf{h}_{m,i} + \mathbf{v}_i \\ &= \begin{bmatrix} \tilde{\mathbf{P}}_{1,i} & \tilde{\mathbf{P}}_{2,i} & \cdots & \tilde{\mathbf{P}}_{M,i} \end{bmatrix} \begin{bmatrix} \mathbf{h}_{1,i} \\ \mathbf{h}_{2,i} \\ \vdots \\ \mathbf{h}_{M,i} \end{bmatrix} + \mathbf{v}_i \\ &= \mathbf{P}_i \mathbf{h}_i + \mathbf{v}_i,\end{aligned} \tag{3}$$

where $\tilde{\mathbf{P}}_{m,i}$ is the $N_p \times N_s$ circular matrix derived from the vector $\mathbf{p}_{m,i}$, $\mathbf{P}_i = \begin{bmatrix} \tilde{\mathbf{P}}_{1,i} & \tilde{\mathbf{P}}_{2,i} & \cdots & \tilde{\mathbf{P}}_{M,i} \end{bmatrix}$ is the $N_p \times MN_s$ training sequence matrix, $\mathbf{h}_i = \begin{bmatrix} \mathbf{h}_{1,i} & \mathbf{h}_{2,i} & \cdots & \mathbf{h}_{M,i} \end{bmatrix}^T$ is the $MN_s \times 1$ channel vector, and $\mathbf{v}_i$ is the AWGN with zero mean and the variance of σ^2.

The maximum likelihood estimation of the channel vector $\mathbf{h}_i$ in (3) is given by [14]

$$\hat{\mathbf{h}}_i = \left(\mathbf{P}_i^H \mathbf{P}_i\right)^{-1} \mathbf{P}_i^H \mathbf{q}_i. \tag{4}$$

The MSE of the channel estimation in (4) is derived as

$$\begin{aligned}MSE &= \frac{1}{MN_s} E\left\{\left(\hat{\mathbf{h}}_i - \mathbf{h}_i\right)^H \left(\hat{\mathbf{h}}_i - \mathbf{h}_i\right)\right\} \\ &= \frac{1}{MN_s} E\left\{\left(\mathbf{P}_i^H \mathbf{P}_i\right)^{-1} \mathbf{P}_i^H \mathbf{v}_i\right\} \\ &= \frac{\sigma^2}{MN_s} tr\left\{\left(\mathbf{P}_i^H \mathbf{P}_i\right)^{-1}\right\}.\end{aligned} \tag{5}$$

The minimum MSE of the channel estimation can be achieved if and only if

$$\mathbf{P}_i^H \mathbf{P}_i = \frac{1}{N_p} \mathbf{I}_{MN_s}. \tag{6}$$

The channel estimation in (4) is then simplified as

$$\hat{\mathbf{h}}_i = \frac{1}{N_p} \mathbf{P}_i^H \mathbf{q}_i = \mathbf{h}_i + \frac{1}{N_p} \mathbf{P}_i^H \mathbf{v}_i, \tag{7}$$

and the corresponding minimum MSE is

$$MSE_{\min} = \frac{\sigma^2}{N_p}. \tag{8}$$

Clearly, the PN sequence used as the training sequence in [7] has good but not ideal circular autocorrelation, thus the requirement denoted by (6) can not be well satisfied and consequently the minimum channel estimation error in (8) could not be achieved. To acquire the minimum MSE of the channel estimation, the CAZAC sequence with perfect circular autocorrelation function is proposed as the training sequence and the signal frame structure design defined by (1) is still reserved. According to [15], the CAZAC sequence $\mathbf{p}_{m,i}$ can be selected as

$$p_{m,i}(n) = \exp\left\{\pi r n^2 / N_p\right\} \quad 0 \le n \le N_p - 1, \tag{9}$$

where r is relatively prime to N_p. The autocorrelation of the CAZAC sequence is

$$R_p(k) = \sum_{n=0}^{N_p-1} p^*_{m,i}(n) p_{m,i}((n+k))_{N_p} = \begin{cases} N_p & k = 0 \\ 0 & k \ne 0 \end{cases}. \tag{10}$$

Therefore, the CAZAC sequence meets the requirement in (6) and the best channel estimation performance can be achieved.

B. Timing Synchronization

The TDS-OFDMA system in [7] works well if the uplink signals from M different users arrive at the base station synchronously. However, timing synchronization must be carefully addressed in actual applications. Unlike the concept of quasi-synchronization in most OFDMA systems [8], the timing synchronization of the TDS-OFDMA system can be investigated together with the channel estimation.

As for the unbiased channel estimation in (7), the matrix multiplication can be also expressed in the form of circular correlation due to the circular property of the training matrix

$$\begin{aligned}\hat{\mathbf{h}}_i &= \frac{1}{N_p}\mathbf{p}_{m,i}\otimes\mathbf{q}_i = \frac{1}{N_p}\mathbf{p}_{m,i}\otimes\left(\sum_{m=1}^{M}\mathbf{p}_{m,i}\otimes\mathbf{h}_{m,i}+\mathbf{v}_i\right)\\ &= \sum_{m=1}^{M}\mathbf{h}_{m,i}\delta[n-(m-1)N_s]+\frac{1}{N_p}\mathbf{p}_{m,i}\otimes\mathbf{v}_i,\end{aligned} \tag{11}$$

where the perfect autocorrelation of the CAZAC sequence is applied.

The circular correlation based channel estimation in (11) is similar to the sliding correlation based timing synchronization in the single-user TDS-OFDM systems [5], whereby one local PN sequence is correlated with the incoming signals to find the correlation peak and then indicate the starting point of each frame with high accuracy. Due to the cyclic extension, the sliding correlation is equal to the circular correlation in (11). The only difference is that, in the multi-user TDS-OFDMA system, multiple user-specific timing errors have to be estimated. Because of the special frame structure of the TDS-OFDMA system in the space dimension defined by (1), the user-specific timing error is converted by the circular correlation into the location shift of the corresponding correlation peak compared with the predefined pattern. Therefore, timing synchronization for multiple users could be simultaneously achieved.

It has been demonstrated in [5] that the timing synchronization based on the training sequence with good autocorrelation would lead to the estimation error within $\pm Ts/2$ (where Ts is the sampling period at the base station receiver) under AWGN and multi-path channels. Therefore, it can be concluded that the time-domain training sequence aided TDS-OFDMA system can achieve accurate timing synchronization and consequently the adoption of quasi-synchronous model could be avoided.

C. Frequency Synchronization

The circular correlation results in (11) can be utilized for the frequency synchronization of the TDS-OFDMA system. The received training sequence $\mathbf{q}_i$ corresponding to the incoming signals from M users with the user-specific frequency errors has the elements

$$q_i(n)=\sum_{m=1}^{M}p_{m,i}(n)\exp\left\{\varepsilon_m n+\left(i-1\right)N_f+N_t\right\}, \tag{12}$$

where ε_m is the user-specific CFO. For simplicity, the noise term is omitted and AWGN channel is assumed.

Considering the frequency errors, the circular correlation results for realizing both channel estimation and timing synchronization would be

$$\begin{aligned}z_i(n) &= \frac{1}{N_p}p_{m,i}(n)\otimes q_i(n)\\ &= \frac{1}{N_p}p_{m,i}(n)\otimes\left\{\sum_{m=1}^{M}p_{m,i}(n)\exp\left\{\varepsilon_m n+\left(i-1\right)N_f+N_t\right\}\right\}\\ &= \exp\left\{\varepsilon_m n+\left(i-1\right)N_f+N_t\right\}\sum_{m=1}^{M}\delta\left[n-(m-1)N_s\right].\end{aligned} \tag{13}$$

The correlation peak corresponding to the mth user in the ith signal frame is

$$z_i\left((m-1)N_s\right)=\exp\left\{\varepsilon_m n+\left(i-1\right)N_f+N_t\right\}\quad 1\le m\le M. \tag{14}$$

Likewise, the correlation peak in the (i+1)th frame is

$$z_{i+1}\left((m-1)N_s\right)=\exp\left\{\varepsilon_m n+iN_f+N_t\right\}\quad 1\le m\le M. \tag{15}$$

Therefore, the user-specific CFOs $\left\{\varepsilon_m\right\}_{m=1}^{M}$ can be estimated according to

$$\hat{\varepsilon}_m=\frac{1}{N_f}\arg\left\{\left[z_i\left((m-1)N_s\right)\right]^*\cdot\left[z_{i+1}\left((m-1)N_s\right)\right]\right\}\quad 1\le m\le M. \tag{16}$$

The Cramer-Rao lower bound (CRLB) of the CFO estimator under AWGN channel is [16]

$$CRLB(\hat{\varepsilon}_m)=\frac{6}{\gamma K^2(K-1)}, \tag{17}$$

where K is the number of data used for frequency synchronization.

Unlike the conventional frequency synchronization schemes that can be only used in the subband CAS type or the interleaved CAS type of OFDMA systems [11], the proposed CFO estimator is applicable to the generalized CAS, because the used correlation peaks are orthogonally separated due to the special frame structure of the TDS-OFDMA system. Therefore, the estimation of all the user-specific CFOs can be simultaneously achieved.

It should be pointed out that the CFO estimator also works under multi-path channels, which will be verified by the simulation results in Section IV. Besides that, the better estimation performance is expected by selecting the most significant correlation peaks corresponding to each user, which can be obtained according to (11).

D. Computational Complexity

The circular correlation for joint channel estimation and timing synchronization in (11) could be implemented by FFT/IFFT operation. Therefore, the computational complexity is $o(N_p\log_2 N_p)$, much lower than the iterative channel estimation in the single-user TDS-OFDM system [6].

Regarding to the frequency synchronization, as shown in Table I, the multiple signal classification (MUSIC) based CFO estimator for the interleaved CAS type of OFDMA systems has the complexity of $o\left(\left(N/M\right)^2N_\varepsilon\right)$ [12], and the SAGE based iterative frequency synchronization has the complexity of $o\left(MNN_g\left(N_\varepsilon+1\right)\right)$ per iteration for the generalized CAS type of OFDMA systems [13], where N_ε is the number of grid points for CFO estimation. However, the proposed frequency synchronization in (16) directly utilizes the correlation peaks obtained during the joint channel estimation and timing synchronization process whose complexity is $o(N_p \log_2 N_p)$. Thus no extra processing is required for CFO estimation.

TABLE I
FREQUENCY SYNCHRONIZATION COMPLEXITY COMPARISON

CFO Estimator	Complexity
MUSIC Based [12]	$o\left(\left(N/M\right)^2 N_\varepsilon\right)$
SAGE Based [13]	$o\left(MNN_g\left(N_\varepsilon+1\right)\right)$
Proposed	$o(N_p \log_2 N_p)$ [2]

IV. SIMULATION RESULTS AND DISCUSSIONS

Simulations are carried out to verify the feasibility and the performance of the joint channel estimation and time-frequency synchronization for the TDS-OFDMA system without channel coding and interleaving. Without generality, four active users are assumed in the TDS-OFDMA system, and four typical multi-path channel models are used, including two DTTB channel models, which are Brazil A and Brazil D [17], and another two ITU-R defined channel models, which are Indoor B and Vehicular A [18]. The channel model selected for user 1, user 2, user 3 and user 4 are Brazil A, Indoor B, Vehicular A, and Brazil D, respectively. The major system parameters for simulation are shown in Table II.

TABLE II
SYSTEM PARAMETERS FOR SIMULATION

Number of Active Users	4
Carrier Allocation Scheme (CAS)	Generalized
System Bandwidth	8 MHz
Symbol Rate	7.56 M symbol/s
Sub-carrier Spacing	2 kHz
Available sub-carriers	3780
Modulation Scheme	QPSK
CAZAC Sequence Length	256
Circular Shift in the Time Dimension	64
Circular Shift in the Space Dimension	64

Fig. 3 compares the MSE performance of the circular correlation based channel estimation for the TDS-OFDMA system with the PN sequence based channel estimation in [7] and the iterative channel estimation for the single-user TDS-OFDM system [6]. As the reference, the theoretical bound from (8) is also included. It is clear that the CAZAC based channel estimation is superior to the PN based method due to the perfect autocorrelation of the CAZAC sequence, and the iterative channel estimation has the worst performance due to the ISI between the PN sequence and the IDFT block. It also shows that the simulated MSE of the proposed channel estimation approaches the theoretical bound.

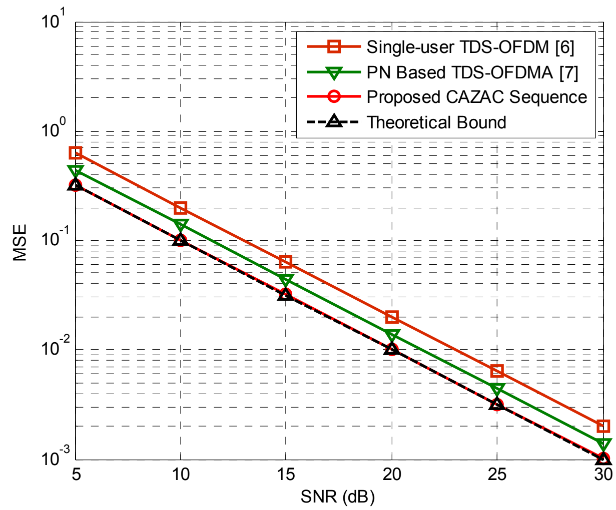

Fig. 3. MSE of the circular correlation based channel estimation under Brazil A channel.

Fig. 4 illustrates an example of the circular correlation based timing synchronization under AWGN channel at the signal-to-noise ratio (SNR) of 0 dB. The CFO of 400 Hz is assumed for each user. Fig. 4 (a) shows the correlation peaks without timing errors, where the positions of the measured peaks are overlapped with the reference pattern known to the base station. Fig. 4 (b) presents the correlation peaks when user 2, user 3 and user 4 have the timing errors of -2 samples, $+3$ samples and -4 samples, respectively. It is clear from Fig. 4 that the user-specific timing errors could be detected by counting the position shifts of the corresponding measured peaks compared with the reference pattern.

Fig. 5 presents the performance of the circular correlation based frequency synchronization method in terms of MSE under both AWGN and multi-path channels. The user-specific CFOs for user 1, user 2, user 3 and user 4 are configured to be 400 Hz, 300 Hz, 200 Hz and 100 Hz, respectively. The CFO under AWGN channel is 500 Hz. The CRLB for the frequency estimation is also shown for comparison. Simulation results indicate that the proposed frequency synchronization method can achieve the MSE below 10^{-4} under both multi-path and AWGN channels when SNR is higher than 0 dB, and the simulated CFO estimation accuracy can achieve the CRLB under AWGN channel.

Fig. 6 shows the bit error rate (BER) performance of the actual TDS-OFDMA system with the estimated CIR and time-frequency parameters under multi-path channels. For comparison, the BER performance of the ideal TDS-OFDMA

[2] This is the complexity for joint channel estimation and time-frequency synchronization.

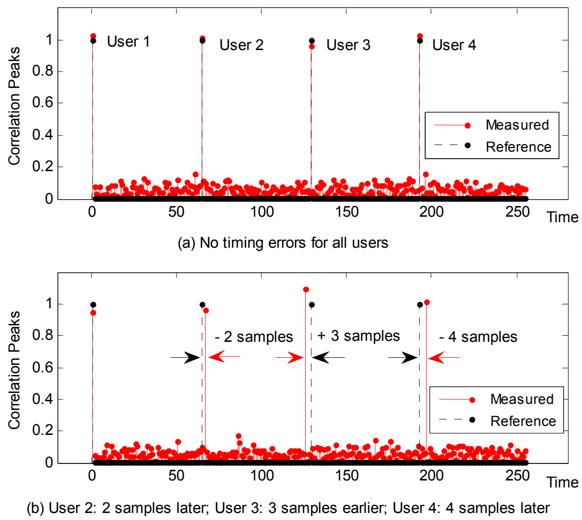

Fig. 4. Correlation peaks for the timing synchronization under AWGN channel with the CFO of 400 Hz at the SNR of 0 dB.

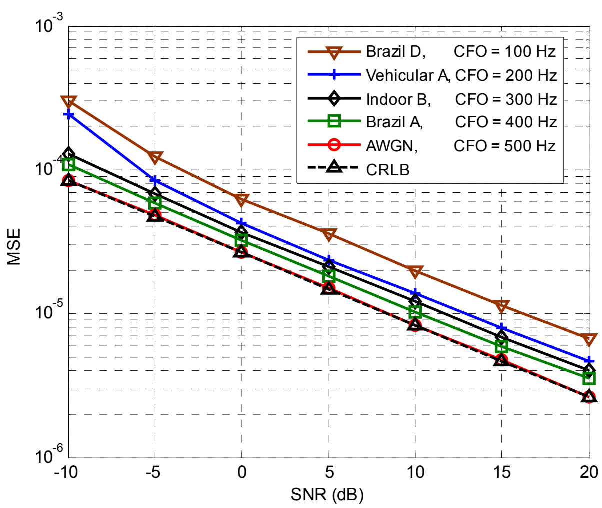

Fig. 5. MSE performance of the circular correlation based joint CFO estimator under AWGN and multi-path channels.

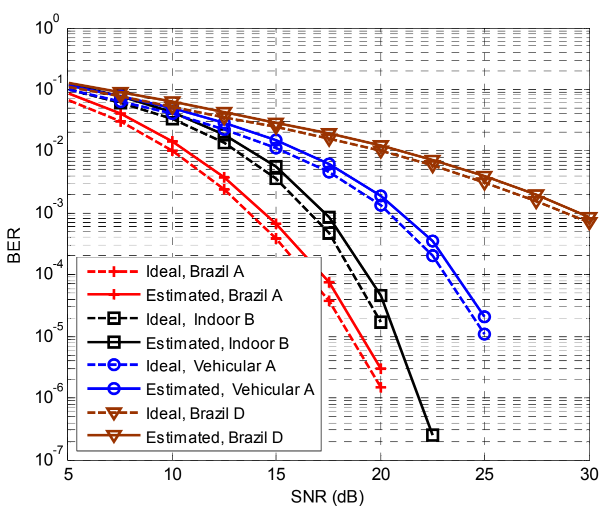

Fig. 6. BER performance of the TDS-OFDMA system under multi-path channels.

system with perfect channel estimation and time-frequency synchronization is also included. Due to the good performance of the proposed channel estimation and time-frequency synchronization scheme, BER performance of the actual TDS-OFDMA system deteriorates a little compared with the ideal cases. The SNR loss caused by practical channel estimation and time-frequency synchronization is about 0.5 dB for the simulated multi-path channels.

V. Conclusions

This paper proposes a joint channel estimation and time-frequency synchronization method for the TDS-OFDM based uplink multiple access scheme called TDS-OFDMA. The "time-space two-dimensional frame structure" of the TDS-OFDMA system and the time-domain CAZAC training sequence having perfect autocorrelation are utilized. Since only the time-domain circular correlation is required, channel estimation and time-frequency synchronization could be simultaneously achieved with low complexity for all the active users. The proposed joint scheme can be used for any type of carrier assignment scheme, which allows for flexible design for the TDS-OFDMA system.

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BIOGRAPHIES

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