ICI-Resilient Cognitive Radio Sequences for Transform Domain Communication Systems

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***Abstract*—Transform domain communication system (TDCS) is a multi-carrier cognitive radio (CR) technique which uses cyclic code shift keying (CCSK) for overlay opportunistic spectrum access. Specifically, at any given time, a TDCS system cyclically shifts a fundamental modulation waveform (i.e., a CR sequence satisfying a dynamic spectrum hole constraint) according to specific input data symbol. In practical TDCS system, an interesting research problem is how to design CR sequence with inter-carrier interference (ICI) resilience, where ICI is caused by carrier frequency offset (CFO) or Doppler spread. In this paper, we present a novel family of CR sequences which are able to achieve ICI self-cancellation in TDCS. Analysis and simulations validate that our proposed CR sequence is effective for ICI suppression in TDCS. A future work of this research is to optimize the peak-to-mean power ratio of such CR sequences.**

***Index Terms*—Cognitive Radio Systems, Spectrum Hole Constraint, Carrier Frequency Offset, Inter-Carrier Interference, Cognitive Radio Sequences, Reliable Communications.**

I. Introduction

It is widely believed that we are running out of the precious spectrum resource. Against such a background, cognitive radio (CR) emerges as a promising paradigm to solve the scarcity of available spectrum bands by using or sharing the spectrum in an opportunistic manner, where the spectrum opportunity is defined as spectrum holes that are not being used by primary user(s) at a particular time and location [1]−[3].

As an overlay CR technique, transform domain communication system (TDCS) has received increasing research attention in recent years. A TDCS assumes that both the transmitter and the receiver see the identical available spectrum bands. This allows a TDCS transmitter to dynamically generate a smart fundamental modulation waveform (FMW) to avoid interference at the transmitter rather than mitigating interference at the receiver [4], [5]. Using cyclic code shift keying (CCSK), a TDCS transmitter sends out a specific cyclic shift of FMW according to the input data symbols at any given time. Correspondingly, the data symbols are recovered in the receiver by detecting the position of the maximum periodic autocorrelation magnitude of the FMW, i.e., noncoherent detection. In short, TDCS is able to provide reliable communication with low probability of interception even certain available spectral bands are invaded by jammers.

A number of research works have been concerned with efficient and robust development of TDCS. In particular, the acquisition and synchronization of TDCS were studied in [6]. An efficient implementation of TDCS was presented in [7] to enhance bit error rate (BER) performance. In addition, there have been cluster-based TDCS [8] and multidimensional TDCS modulation scheme [9] for higher spectral efficiency.

To support multiuser communications, multiple access TDCS (MA-TDCS) has been proposed by assigning each user a unique m-sequence from a distinct primitive polynomial [10]. From sequence design point of view, [11] first studied multiuser interference (MUI) avoidance in MA-TDCS, to our best knowledge. Specifically, MUI avoidance is achieved by constructing almost perfect CR sequences based on a time-frequency synthesis. Very recently, Hu and Liu *et al* developed CR sequences with zero cross-correlation zone property and with low peak-to-average power ratios [12]. It has been shown that such CR sequences are capable of supporting interference-free CR-CDMA communications.

It is noted that TDCS will suffer from inter-carrier interference (ICI) when CFO and/or Doppler spread are/is present. This is because TDCS, as a special type of multicarrier system, requires precise frequency synchronization; otherwise, the orthogonality among TDCS subcarriers will be lost, resulting in ICI. Up to date, however, ICI-resilient TDCS is still open. The major objective of this paper is to present a novel family of CR sequences to enable ICI-resilient TDCS.

For traditional multicarrier systems such as orthogonal frequency-division multiplexing (OFDM) systems, there have been three different approaches for ICI suppression: (1) frequency-domain equalization [13]; (2) time-domain windowing [14]; (3) ICI self-cancellation [15]. For the ICI self-cancellation scheme, each data symbol is modulated onto a group of adjacent subcarriers. Although such group mapping results in rate reduction of an OFDM system, it admits a natural match with TDCS with no rate loss, owing to CCSK modulation property. Motivated by this observation, we propose a novel design of CR sequence for ICI-resilient TDCS based on the ICI self-cancellation scheme in [15]. Our proposed CR sequence can be also used for other CR applications, such as training sequences for channel estimation and synchronization in the presence of CFO and/or Doppler spread.

This paper is organized as follows. In Section II, we give an overview of TDCS. In Section III, we analyze the ICI problem in TDCS and present ICI-resilient CR sequences, followed by simulation results in Section IV. In this end, this paper is summarized in Section V.

II. Overview of TDCS

In a CR scenario, a spectrum opportunity is defined as the spectral bands which are not being used by the designated primary users at a particular time and location. In this paper, we assume that the entire spectrum is divided into N subcarriers, and a "subcarrier marking vector" $\mathcal{M} = [m_0, m_1, \cdots, m_{N-1}]^{\mathrm{T}}$ gives the availability status of all subcarriers. For example, the value of m_k is set to 1 if the kth subcarrier is available; otherwise, $m_k = 0$. Moreover, denote by Ω the set of all unavailable subcarrier positions, i.e., $\Omega = \{k \mid m_k = 0\}$. In this paper, Ω is also referred to as a "spectrum hole constraint".

For the TDCS transmitter shown in Fig. 1, let

$$\mathbf{B} = [B_0, B_1, \cdots, B_k, \cdots, B_{N-1}]^{\mathrm{T}},$$

be a length-N pesudorandom complex-valued *frequency-domain* sequences, which satisfies the spectrum hole constraint, i.e.,

$$B_k = 0 \text{ for } k \in \Omega. \tag{1}$$

Throughout this paper, define $\omega_N = \exp\left(\sqrt{-1}2\pi/N\right)$. Denote by $\mathcal{F}_N = [f_{\mu,\nu}]_{\mu,\nu=0}^{N-1}$ the (scaled) discrete fast Fourier transform (FFT) matrix of order N, i.e.,

$$f_{\mu,\nu} = \frac{1}{\sqrt{N}}\omega_N^{-\mu\nu}, \quad 0 \le \mu, \nu \le N-1. \tag{2}$$

Note that $\mathcal{F}_N$ is a unitary matrix, i.e., $\mathcal{F}_N\mathcal{F}_N^{\mathrm{H}} = \mathcal{I}_N$ and $\mathcal{F}_N^{\mathrm{H}} = \mathcal{F}_N^{-1}$. Consequently, the *time-domain* fundamental modulation waveform of $\mathbf{B}$ can be expressed as

$$\begin{aligned} \mathbf{b} &= [b_0, b_1, \cdots, b_n, \cdots, b_{N-1}]^{\mathrm{T}} = \lambda\mathcal{F}_N^{-1}\mathbf{B}, \\ b_n &= \lambda\sum_{k=0}^{N-1} m_k B_k \omega_N^{kn} \qquad (3) \\ &= \frac{1}{\sqrt{N-|\Omega|}}\sum_{k\notin\Omega} B_k\omega_N^{kn}, \qquad (4) \end{aligned}$$

where $\lambda = \sqrt{\frac{N}{N-|\Omega|}}$ is a normalization factor to ensure transmitted signal having the normalized energy. In this paper, a sequence which satisfies the spectrum hole constraint in a CR system is called a *CR sequence*, to distinguish it from the traditional sequences with no spectrum hole constraint. When M-ary CCSK is adopted, the transmitted signal $\mathbf{x}$ is obtained by cyclically shifting $\mathbf{b}$ to the right by $\tau_D \in \{0, 1, \cdots, N-1\}$ positions according to the input data symbol D [16],

$$\begin{aligned} \mathbf{x} &= [x_0, x_1, \cdots, x_{N-1}]^{\mathrm{T}}, \\ &= [b_{N-\tau_D}, b_{N-\tau_D+1}, \cdots, b_{N-\tau_D-1}]. \end{aligned} \tag{5}$$

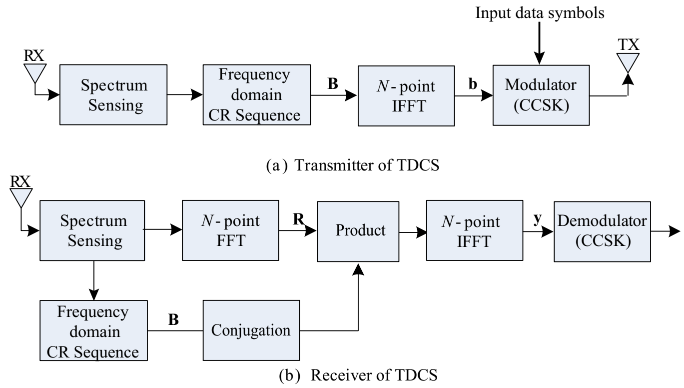

Fig. 1. Block diagram of TDCS transceiver

To recover the transmitted data symbols, the received signal $\mathbf{r} = [r_0, r_1, \cdots, r_{N-1}]^{\mathrm{T}}$ is periodically correlated with the local reference CR sequence by detecting the position of the maximum periodic auto-correlation function (PACF) magnitude [7]. By Wiener-Khinchin Theorem, we note that the power spectrum, denoted by $\boldsymbol{\beta} = [|B_0|^2, |B_1|^2, \cdots, |B_{N-1}|^2]^{\mathrm{T}}$, and the PACF form a Fourier transform pair. Therefore, the PACF (denoted by $\mathbf{y}$) can be calculated using DFT for low computational complexity [16], i.e.,

$$\mathbf{y} = [y_0, y_1, \cdots, y_\tau, \cdots, y_{N-1}]^{\mathrm{T}} = \mathcal{F}_N^{-1} \cdot \mathbf{R} \cdot \mathbf{B}^*, \tag{6}$$

where $\mathbf{R}$ is the received signal in frequency-domain, i.e.,

$$\begin{aligned} \mathbf{R} &= [R_0, R_1, \cdots, R_{N-1}]^{\mathrm{T}} = \mathcal{F}_N\mathbf{r}, \\ R_k &= B_k\omega_N^{-k\tau_D} + n_k, \end{aligned} \tag{7}$$

where n_k denotes the noise component at the kth subcarrier. For ease of presentation, denote by $\hat{B}_k$, the first term of R_k, the equivalent transmitted data at the kth subcarrier by taking into account of the CCSK modulation, i.e.,

$$\hat{B}_k = B_k\omega_N^{-k\tau_D}. \tag{8}$$

Also, we define PACF peak-to-sidelobe ratio (PSR) as follows.

$$\text{PSR} = \frac{\max_\tau\{|y_\tau|\}}{\sum_\tau |y_\tau| - \max_\tau\{|y_\tau|\}}. \tag{9}$$

Finally, the transmitted data symbol (i.e., D) is recovered by

$$\hat{D} = \arg\max_{\tau\in\{0,1,\cdots,N-1\}}\{|\mathbf{y}|\}. \tag{10}$$

Clearly, a higher PSR will lead to better detection performance of D. It is also interesting to note that TDCS signals have a low probability of interception for unauthorized listeners. This is because every data symbol D is hidden in the background noise by spreading over all available subcarriers. The interested reader is referred to [5] and [11] for more details of TDCS.

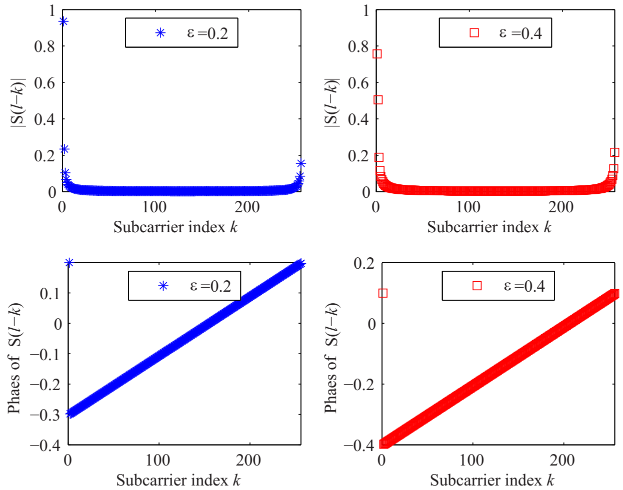

Fig. 2. Amplitude and phase of S_{l-k} for $N = 256$ and $l = 0$.

III. Design of CR Sequences with ICI Resilience

A. Analysis of ICI in TDCS

In this subsection, we analyze ICI in TDCS typically caused by CFO. Since TDCS is a special multicarrier system under a spectral hole constraint, the effect of CFO can be modeled as that in traditional multicarrier systems. Denote by f_d and f_s the CFO and the subcarrier spacing, respectively. Furthermore, denote by ε the normalized CFO, i.e., $\varepsilon = f_d/f_s$. Consequently, the received signal on the kth available subcarrier R_k in (7) can be rewritten as [17]

$$R_k = \hat{B}_k S_0 + \underbrace{\sum_{l=0, l\neq k}^{N-1} \hat{B}_l S_{l-k}}_{\text{ICI}} + \hat{n}_k, \quad l, k \notin \Omega, \tag{11}$$

where $\hat{n}_k$ the corresponding noise component, and S_{l-k} the ICI coefficient between lth and kth subcarriers which can be expressed as

$$S_{l-k} = \frac{\sin\left(\pi\left(l+\varepsilon-k\right)\right)}{N\sin\left(\frac{\pi}{N}\left(l+\varepsilon-k\right)\right)} \exp\left(\frac{j\pi(N-1)(l+\varepsilon-k)}{N}\right). \tag{12}$$

Substituting (11) into (6) and by (10), the transmitted symbol D is detected by the following equation.

$$\hat{D} = \underset{\tau\in\{0,1,\cdots,N-1\}}{\arg\max} \left\{ \left| \underbrace{S_0 \cdot \mathcal{F}_N^{-1} \cdot \hat{\boldsymbol{\beta}}}_{\text{desired part}} + \mathcal{I}_{\text{ICI}} + \mathcal{I}_{\text{noise}} \right| \right\} \tag{13}$$

where

$$\hat{\boldsymbol{\beta}} = \left[\left|B_0\right|^2 \omega_N^{-0\cdot\tau_D}, \left|B_1\right|^2 \omega_N^{-1\cdot\tau_D}, \cdots, \left|B_{N-1}\right|^2 \omega_N^{-(N-1)\cdot\tau_D}\right]^{\mathrm{T}} \tag{14}$$

denotes the power spectrum of $\mathbf{b}$ modulated by a phase rotation vector caused by the cyclic shift of τ_D and $\mathcal{I}_{\text{ICI}} = [I_0, I_1, \cdots, I_{N-1}]^{\mathrm{T}}$ denotes the ICI vector with

$$I_\tau = \frac{1}{\sqrt{N}} \sum_{k\notin\Omega} \sum_{l\notin\Omega, l\neq k} B_l B_k^* S_{l-k} \omega_N^{k\tau - l\tau_D} \tag{15}$$

and $\mathcal{I}_{\text{noise}}$ denotes the corresponding noise vector.

B. Proposed ICI-resilient CR sequences

In this part, we present a design of ICI-resilient CR sequences for TDCS system. Specifically, we wish to design CR sequence $\mathbf{B}$ such that the desired part in (13) is less sensitive to nonzero CFO while the ICI part (i.e., $\mathcal{I}_{\text{ICI}}$) can be suppressed.

From Section II.B, it is clear that if $\varepsilon = 0$, we have $S_0 = 1$ and $S_{l-k} = 0$ $(l \neq k)$, and hence zero-ICI; Nevertheless, as ε becomes larger, the magnitude of S_0 decreases and S_{l-k} $(l \neq k)$ increases, resulting in nonzero-ICI and thus a degradation of the effective signal-to-noise ratio (SNR) for TDCS demodulation. To gain a simple insight of the ICI effect, two examples of S_{l-k} for $\varepsilon \in \{0.2, 0.4\}$ are shown in Fig. 2. We have the following two observations.

- $|S_1|$ and $|S_2|$ have comparable values with $|S_0|$. For example, $|S_1| = 0.2$ and $|S_2| = 0.1$ for $\varepsilon = 0.2$, while $|S_1| = 0.5$ and $|S_2| = 0.2$ for $\varepsilon = 0.4$. In addition, other ICI coefficients have relative small values which can be negligible, i.e., $|S_k| \approx 0, k \geq 4$;
- The adjacent ICI coefficients of S_0 have negative phases. Specifically, $\angle S_0 = -0.2$ (rad) and $\angle S_1 \approx \angle S_2 = -0.3$ (rad) for $\varepsilon = 0.2$, while $\angle S_0 = -0.1$ (rad) and $\angle S_1 \approx \angle S_2 = -0.4$ (rad) for $\varepsilon = 0.4$.

Motivated by the above observations, we consider the ICI-cancellation scheme in [15] by transmitting pairs of (B_{2k}, B_{2k+1}) with identical magnitude but opposite signs, i.e.,

$$\mathbf{B} = \left[B_0, -B_0, \cdots, B_k, -B_k, \cdots, B_{N/2-1}, -B_{N/2-1}\right]^{\mathrm{T}}. \tag{16}$$

Intuitively, ICI-cancellation is possible because S_{l-k} and S_{l-k+1} have small difference for a majority of $l-k$ which leads to smaller ICI by the proposed CR sequence in (16). A comparison of the proposed CR sequence and the traditional one is shown shown in Fig. 3.

As a result, I_τ in (15) can be rewritten as

$$\begin{aligned} I_\tau &= -\frac{1}{\sqrt{N}} \sum_{k\notin\Omega,\text{even}} |B_k|^2 S_1 \omega_N^{k\tau-(k+1)\tau_D} + I_\tau^{\text{new}} \\ &= -\frac{1}{\sqrt{N}} S_1 \omega_N^{-\tau_D} \sum_{k\notin\Omega,\text{even}} \left(|B_k|^2 \omega_N^{-k\tau_D}\right) \cdot \omega_N^{k\tau} + I_\tau^{\text{new}} \\ &= -\frac{S_1 \omega_N^{-\tau_D}}{1+\omega^{\tau-\tau_D}} \underbrace{\frac{1}{\sqrt{N}} \sum_{k\notin\Omega} \left(|B_k|^2 \omega_N^{-k\tau_D}\right) \cdot \omega_N^{k\tau}}_{\text{the } \tau\text{th element of } \mathcal{F}_N^{-1}\cdot\hat{\boldsymbol{\beta}}} + I_\tau^{\text{new}}, \end{aligned} \tag{17}$$

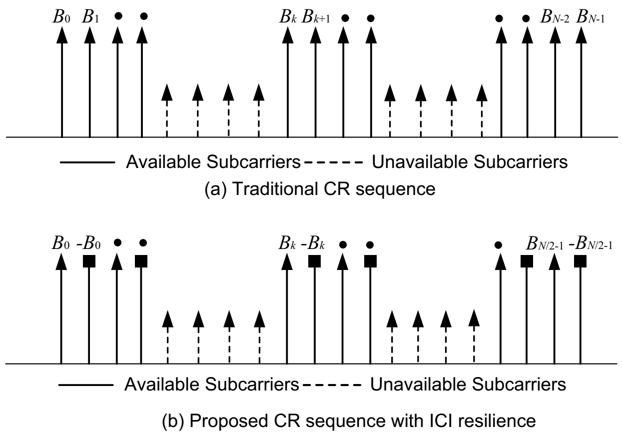

Fig. 3. Examples of the proposed ICI-resilient CR sequence and a traditional one in frequency-domain, where N is an even number.

where

$$I_\tau^{\text{new}} = \frac{1}{\sqrt{N}} \sum_{k \notin \Omega, \text{odd}} B_{k+1} B_k^* S_1 \omega_N^{k\tau - (k+1)\tau_D} + \frac{1}{\sqrt{N}} \sum_{k \notin \Omega} \sum_{\substack{l \notin \Omega \\ l \neq k, k+1}} B_l B_k^* S_{l-k} \omega_N^{k\tau - l\tau_D}. \quad (18)$$

Remark 1: One can see that the CR sequence in (16) allows us to create another desired term which contains $\mathcal{F}_N^{-1}\hat{\boldsymbol{\beta}}$ from the ICI part in (15) to back up the "desired part" in (13), while enjoying I_τ^{new} with less ICI.

Let $\mathbf{I}_N$ be the identity matrix of order N. Further, let $\mathbf{Q}_{\tau_D} = \text{Diag}(\mathbf{x}_{\tau_\mathbf{D}})$ be a diagonal matrix with

$$\mathbf{x}_{\tau_D} = \left[\frac{1}{1+\omega^{0-\tau_D}}, \frac{1}{1+\omega^{1-\tau_D}}, \cdots, \frac{1}{1+\omega^{N-1-\tau_D}}\right]^{\text{T}} \quad (19)$$

being the diagonal vector. In addition, define

$$\mathcal{I}_{\text{ICI}}^{\text{new}} = \left[I_0^{\text{new}}, I_1^{\text{new}}, \cdots, I_{N-1}^{\text{new}}\right]^{\text{T}}.$$

Thus, the detection function (13) will further reduce to (20).

Example 1: Let $N = 64$ and $\mathcal{M} = [\mathbf{1}_{14}, \mathbf{0}_6, \mathbf{1}_{20}, \mathbf{0}_8, \mathbf{1}_{16}]^{\text{T}}$ be the subcarrier marking vector. Thus,

$$\Omega = \{14, 15, \cdots, 19\} \cup \{40, 41, \cdots, 47\}.$$

For any given normalized CFO ε, we construct $\mathbf{B}_{\text{prop}}$ (a proposed CR sequence) and $\mathbf{B}_{\text{trad}}$ (a traditional one), both of which satisfying the spectrum hole constraint Ω.

$$\mathbf{B}_{\text{prop}} = \left[\hat{B}_0, -\hat{B}_0, \cdots, \hat{B}_k, -\hat{B}_k, \cdots, \hat{B}_{31}, -\hat{B}_{31}\right]^{\text{T}},$$
$$\mathbf{B}_{\text{trad}} = [B_0, +B_1, \cdots, B_{2k}, +B_{2k+1}, \cdots, B_{62}, +B_{63}]^{\text{T}},$$

In addition, provided that a specific entry of $\mathbf{B}_{\text{prop}}$ corresponds to an available subcarrier position, such entry will be assigned a random phase and identical magnitude of $\sqrt{\frac{N}{N-|\Omega|}}$. The same can be said for $\mathbf{B}_{\text{trad}}$. To evaluate the ICI resilience of both CR sequences, we assume the channel is noise-free and consider the PACF PSR as defined in (9). Then, we plot PSR versus normalized CFO ε, as shown in Fig. 4. One can see that as ε ranges from $[-0.5, 0.5]$, our proposed CR sequence is more ICI-resilient because its PACF PSR drops slower than that of the traditional one.

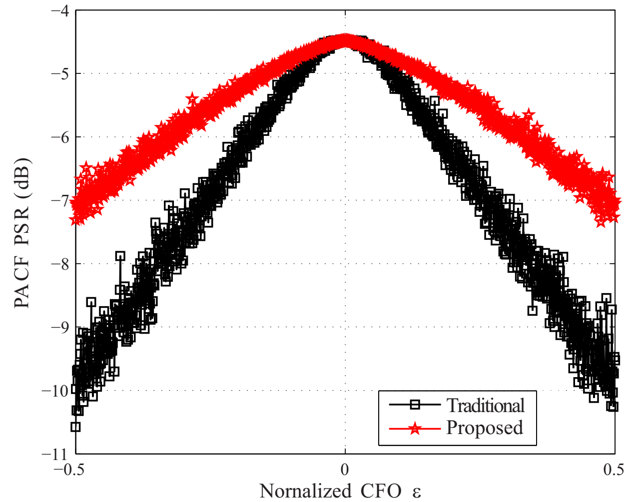

Fig. 4. PACF PSR versus normalized CFO ε for CR sequences $\mathbf{B}_{\text{prop}}$ (proposed) and $\mathbf{B}_{\text{trad}}$ (traditional).

TABLE I
SIMULATION SETTINGS

Parameters	Traditional TDCS	Proposed TDCS
CR sequences	Zadoff-Chu sequences	ICI-resilient sequences
Sequence of length	256	256
Modulation	64-ary CCSK	64-ary CCSK
Entire bandwidth	10MHz	
Unavailable bands	2.5∼3.75 MHz and 6.25∼7.5 MHz	
Channel A	AWGN+CFO	
Channel B	COST207RAx6+Doppler Spread [18]	
Receiver	MMSE-FDE	MMSE-FDE

IV. SIMULATION RESULTS

In this section, we compare BER performances of TDCS systems using two different types of CR sequences, namely, Zadoff-Chu based CR sequences and our proposed ICI-resilient CR sequences. To validate the ICI resilience, both AWGN and multipath fading channels are considered. When passing through a multipath fading channel, a cyclic prefix (CP) should be inserted in the transmitter to prevent inter-symbol interference (ISI), while an equalizer should be placed after the FFT block in the receiver to compensate the frequency-selectivity. In particular, we considered AWGN channel with CFO and multipath fading channel with Doppler spreading. The system configuration of TDCS is shown in Table. I.

Fig. 5 shows BER performances of uncoded TDCS with different CR sequences. When Zadoff-Chu based CR sequence is employed, it is clear that the BER performance becomes unacceptable when CFO is increased from $\varepsilon = 0.2$ to 0.4. When $\varepsilon = 0.4$, the traditional TDCS has a high error floor

$$\hat{D} = \arg \max_{\tau \in \{0,1,\cdots,N-1\}} \left\{ \left| \underbrace{\left(S_0 \mathbf{I}_N - S_1 \omega_N^{-\tau_D} \mathbf{Q}_{\tau_D}\right) \cdot \mathcal{F}_N^{-1} \cdot \hat{\boldsymbol{\beta}}}_{\text{desired part}} + \mathcal{I}_{\text{ICI}}^{\text{new}} + \mathcal{I}_{\text{noise}} \right| \right\}. \tag{20}$$

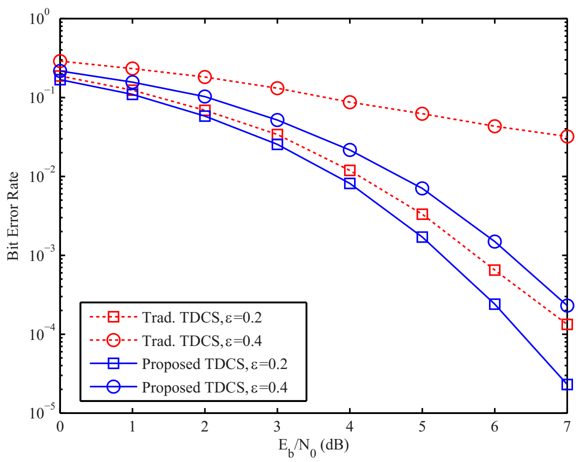

Fig. 5. BER performance of uncoded TDCS with different CR sequences in AWGN channel with CFO (Channel A)

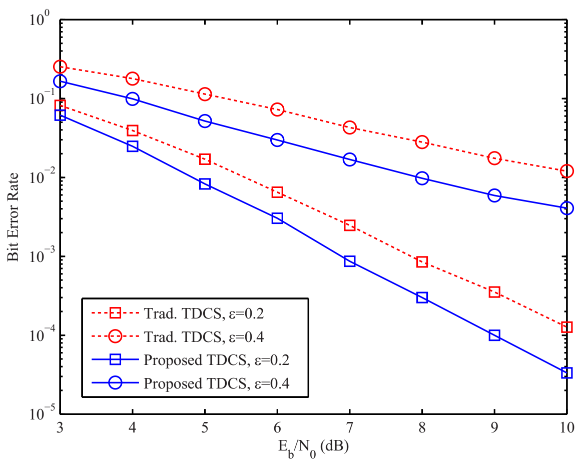

Fig. 6. BER performance of coded TDCS with different CR sequences in multipath fading channel with Doppler spread (Channel B)

because of large ICI. In comparison, when our proposed CR sequence is adopted, TDCS achieves more robust BER performance than the traditional one. When ε changes from 0.2 to 0.4, there is only 1dB BER performance loss, indicating that TDCS with the proposed CR sequence is an effective scheme against CFO in AWGN channel.

Let us discuss BER performances of coded TDCS with different CR sequences in multipath fading channel (COST207RAx6 channel in [18]). A convolutional code with code rate of $1/2$ is used. To combat with ISI, a CP which has width $1/4$ of the total symbol duration and a minimal mean square error (MMSE) equalizer are adopted. The maximum Doppler spread $f_d \in \{0.2, 0.4\}$ is considered. It is clear that, even in multipath fading channels, TDCS employing the proposed CR sequence is capable of achieving better BER performance than traditional TDCS. For example, when $\varepsilon = 0.2$, our proposed TDCS scheme has a 1.1dB performance gain at BER=10^{-3}.

V. Conclusions

In this paper, we have designed a class of ICI-resilient CR sequences for TDCS transmission. Such a design requires transmitting pairs of adjacent subcarriers with identical magnitude and opposite signs, leading to ICI self-cancellation. Analysis and simulations show that our proposed ICI-resilient CR sequences are robust to CFO and/or Doppler spread in TDCS systems. In addition, our proposed CR sequences may have applications in Doppler-resilient channel estimation or synchronization in various spectrally constrained systems.

For the practicality of TDCS, a future work of this research is to further optimize the peak-to-average power ratio (PAPR) of CR sequences. It is interesting to note that the idea of ICI self-cancellation, which first appeared in [15] and further exploited in this paper, is somewhat similar to that of Golay complementary pair [19], a pair of sequences whose out-of-phase aperiodic auto-correlations sum to zero. The interested reader may refer to [20]−[26] for perfect-/quasi- complementary sequences. Since each Golay complementary sequences has a PAPR of at most 2, it may be interesting to investigate how complementary sequences can further benefit the ICI-resilient CR sequence design for TDCS transmission.

Acknowledgment

The work of Su Hu and Shu Fang is supported by the National High-Tech R&D Program of China ("863" Project under Grant number 2014AA01A707), Natural Science Foundation of China (61101090/61471100/61401074). The work of Zilong Liu and Yong Liang Guan was supported by the Advanced Communications Research Program DSOCL14095, a research grant from the Future Systems and Technology Directorate, MINDEF, Singapore.

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