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TDCS-IDMA System for Cognitive Radio Networks With Cloud

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ABSTRACT Cognitive radio (CR) is a novel technology for improving the utilization of radio electromagnetic spectrum. Recently, a new model called cognitive radio networks with cloud (CRNC) has been proposed to eliminate the constraints (pertinent to traditional CR) on power, memory space, and computational capacity. To enable multiple access of CRNC system, orthogonal frequency division multiplexing-interleave division multiple access (OFDM-IDMA) has been investigated. Traditional OFDM-IDMA may not be applied to CRNC in a straightforward manner. This is because the spectral nulling in CR and the subsequent spectral sensing mismatch (between CR transmitter and receiver) could lead to unacceptable data error performance. This paper presents a new multiple access communication system, called transform domain communication system IDMA communication system, to deal with spectral nulling problems. Two improved schemes based on BPSK and cyclic code shift keying modulations are proposed. The proposed system structure integrates the advantages of both OFDM-IDMA and CRNC, which can make full use of other users' information while satisfying CR constraints. Simulation results demonstrate that the two proposed system architectures can achieve significant improvement on BER performance, multiple access capability, and anti-interference ability with spectral nulling.

INDEX TERMS Cognitive radio, cloud computing, interleave division multiple access, transform domain communication system, spectral nulling.

I. INTRODUCTION

With increasing demand of wireless radio spectrum, fixed spectrum assignment policy leads to spectrum scarcity worldwide. However, most portion of spectrum is inefficiently used, which urges the development of dynamic spectrum access techniques [1]. The concept of cognitive radio (CR) is proposed as a possible solution to solve the spectral congestion problem. It provides the capability to utilize spectrum bands more efficiently in an opportunistic manner without much interruptions to primary users [2]–[4]. In the cognitive radio networks (CRNs), sensors are used to detect the presence of licensed users and find spectrum holes for dynamic spectrum access. Traditional spectrum sensing is usually carried out by CR nodes. This procedure requires complex computation and sufficient storage space to download software packages.

Recently, cloud computing technology has been developed rapidly. The term ''cloud computing'' is defined as using computing logistical resources, as well as software level, through services transported over the Internet. It is considered as a potential solution to CRNs problems [5], [6]. Once the CRNs testbed is connected to the cloud, the data are stored and processed in shared environments and sensors are required to report real-time information to cloud providers. In the meantime, cloud computing provides computing services through the Internet [7], [8].

The convergence of CRNs and cloud computing helps to eliminate current problems in transmission of information. Various multiple access technologies have been developed to enhance multiple access capability in CR scenarios [9], [10]. As an excellent multiple access technology with low complexity, interleave division multiple access (IDMA) outperforms traditional code division multiple access in terms of power and bandwidth efficiency [11]. By combining with orthogonal frequency division multiplexing (OFDM) to provide immunity to multipath fading and impulse noise, OFDM-IDMA system can effectively mitigate the inter-symbol interference (ISI) and suppress the multiple access interference (MAI) simultaneously [12], [13].

Due to the special structure, OFDM-IDMA system has been applied in different fields and attracted wide research interests. As a multicarrier communication system, efficient and novel algorithms for subcarrier and power allocation based on OFDM-IDMA system are investigated [14]–[16]. When compared with traditional alternative algorithms, such as equal power allocation and water filling power allocation, the proposed allocation algorithm in [17] is proved to be superior in terms of communication performance and robustness. Furthermore, a comparison given in [18] between OFDM-IDMA and OFDM-CDMA system shows that OFDM-IDMA has better error probability than OFDM-CDMA. On the other hand, several papers have investigated the application of OFDM-IDMA system in femtocell networks and the performance can be enhanced by grouping the users into femto user and macro user with the random interleaver [19], [20].

Till now, the application of OFDM-IDMA to CR system has not been investigated as traditional OFDM-IDMA cannot maintain robustness in the presence of spectral nulling [21]. For the purpose of providing high data rates and avoiding interference to primary users simultaneously, a special OFDM, known as non-contiguous OFDM system, was proposed to achieve good performance by aggregating non-contiguous blocks of subcarriers [22], [23].

Being one of the CR transceiver technologies, transform domain communication system (TDCS) designs communication signal in frequency domain. It can actively avoid jammed frequencies by environmental sampling, spectral estimation and spectral nulling [24]–[26]. In this paper, TDCS-IDMA for CRNs with cloud (CRNC) is investigated, which can achieve dynamic multiple access of CRNC and improve the robustness of OFDM-IDMA system with spectral nulling. We specifically investigate the spectrum sensing and interleaver design of TDCS-IDMA, and propose the transceiver structure to eliminate the effect of spectral nulling. Based on spectrum sensing and specific interleaver design module, TDCS-IDMA is able to share and access dynamic spectrum with low complexity.

IDMA system mostly uses BPSK modulation or QPSK modulation. Thus, the user capacity and multiple iterations are the main drawbacks of the system. Since IDMA is a spread spectrum communication system essentially, its communication performance degrades rapidly when the number of users is larger than the length of spread sequence. Furthermore, it takes several iterations to eliminate interference. To deal with these problems, an improved system framework based on Cyclic Code Shift Keying (CCSK) is further proposed in this paper, i.e., TDCS-IDMA system with CCSK modulation. Users and subcarriers are divided into groups and each group's data are only transmitted on specific subcarriers. CCSK modulation and user grouping are applied to IDMA system to increase user capacity. Simulations are performed to verify the performance of TDCS-IDMA under interference environments. It is observed that the proposed system can enhance multiple access capability, reduce the complexity of receiver and improve anti-interference ability simultaneously.

The paper is organized as follows. Section II proposes the transmitter and receiver structures of TDCS-IDMA system with BPSK modulation, and introduces its spectrum sensing module, low-cost chip-by-chip iterative multiuser detection algorithm and multiple access capability in detail. Section III presents the system architecture of TDCS-IDMA framework with CCSK modulation, and proposes the transceiver structure. In Section IV, comprehensive simulation results are illustrated, and the effects of number of interleaves, users and different interference signal on communication performances are discussed. Finally, conclusions are made in Section V.

II. TDCS-IDMA SYSTEM WITH BPSK MODULATION

Under the framework of CRNC, cloud database can process and store the information of CR nodes. The transmitter receives surrounding electromagnetic information from cloud database to determine the availability of spectrum based on certain criteria [27], [28]. Assuming the entire spectrum band is divided into N subcarriers. A spectrum marking vector, $\mathbf{A} = [A_0, A_1, \cdots, A_n, \cdots, A_{N-1}]$ is used to indicate the status of subcarriers. For example, if the spectrum sensing result for the n-th subcarrier is smaller (or larger) than a given threshold, the value of A_n is set to 1 (or 0) [26], as shown in Fig. 1.

A. TRANSMITTER STRUCTURE OF TDCS-IDMA SYSTEM WITH BPSK MODULATION

Fig. 2 shows the transmitter of TDCS-IDMA system with BPSK modulation for K simultaneous users. From the structure, the transmitter mainly consists of three modules: forward error correction (FEC) encoder, frequency spreader and interleaver. IDMA relies on interleaving as the exclusive

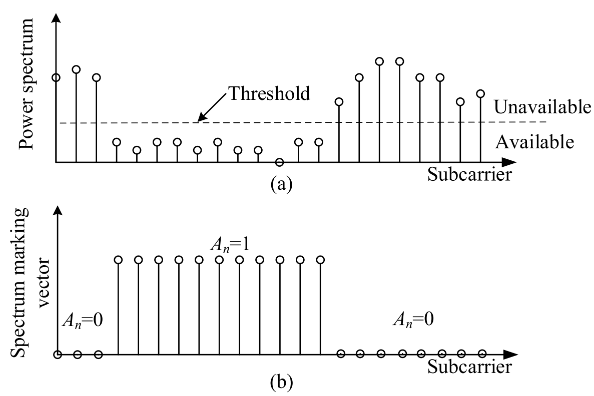

FIGURE 1. Spectrum sensing result. (a) Spectrum scanning. (b) Spectrum decision.

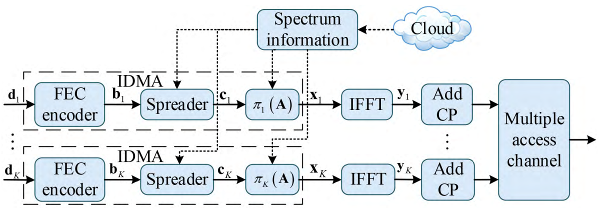

FIGURE 2. Block diagram of transmitter for TDCS-IDMA system with BPSK modulation.

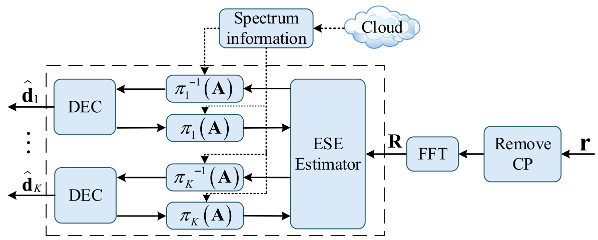

FIGURE 3. Block diagram of receiver for TDCS-IDMA system with BPSK modulation.

method to distinguish signals from other different users [11]. Assuming all the users are in the same electromagnetic environment, the same FEC encoder and spreading code can be used for all users. The interleavers for different users are randomly generated according to the avaliability of spectrum to disperse the coded sequences so that adjacent chips are approximately uncorrelated, which facilitates the simple chip-by-chip detection scheme discussed below [22].

At the transmitter of the k-th user, the information bits $\mathbf{d}_k$ are first encoded to get coded bits $\mathbf{b}_k$. Then the coded bits are spread by a spreading sequence $\mathbf{s} = [s_0, s_1, \cdots, s_{s-1}]$, where S is the length of spreading sequence and the bits after spreading are denoted as $\mathbf{c}_k$ [29]. For the k-th user, the spectrum status is considered when mapping the spreading bits with spectrum bins. The n-th spectrum bin is skipped if the corresponding spectrum marking value $A_n = 0$.

The chips are interleaved by a random interleaver $\pi_k(\mathbf{A})$ to produce the transmit signal for the k-th user $\mathbf{x}_k = [x_0, x_1, \cdots, x_{N-1}]$, where N is the chip length. The interleavers, noted as $\pi(\mathbf{A})$, are generated based on the spectrum marking vector to scramble the order in available spectrum bins. Afterwards, the time-domain signal for the k-th user is obtained by performing an N point inverse fast Fourier transform (IFFT):

$$y_k(m) = \frac{1}{N}\sum_{n=0}^{N-1} A_n x_k(n) e^{\frac{j2\pi mn}{N}}, \quad m = 0, 1, \cdots, N-1. \tag{1}$$

where $x_k(n)$ is the n-th symbol of k-th user.

Finally, the transmitting signal is ready for transmission after adding cyclic prefix. The multiuser TDCS-IDMA system structure processes data in frequency domain and has two special features. The first one is that data should not be transmitted in those subcarriers with $A_n = 0$. The second one is the design of interleaver should take spectrum marking vector into consideration. Since the data sent in occupied spectrum bins are invalid under CR constraints while data sent in unoccupied spectrum bins should be still available after interleave.

B. RECEIVER STRUCTURE OF TDCS-IDMA SYSTEM WITH BPSK MODULATION

The receiving structure is shown in Fig. 3, which consists of an elementary signal estimator (ESE) and K single-user a posteriori probability decoders (DECs). The receiver acquires surrounding electromagnetic information from cloud database and gets a spectrum marking vector, $\mathbf{B} = [B_0, B_1, \cdots, B_k, \cdots, B_{N-1}]$, after determining available spectrum. Here, we assume the transmitter and receiver spectrum sensing results $\mathbf{A}$ and $\mathbf{B}$ are identical. Essentially, the receiver iteratively and alternatively removes MAI for each user by the ESE module and updates the soft estimation of the information bits by the decoder [4], [29]. The received signal performs fast Fourier transform (FFT) operation after removing cyclic prefix to obtain the signal in the frequency domain. Then the multiuser iterative detection algorithm is performed.

The received signals in time domain are represented as

$$r(m) = \sum_{k=1}^{K} h_k(m) \otimes y_k(m) + w(m), \tag{2}$$

where $\otimes$ represents convolution operation and $h_k(m)$ is the time domain impulse response for the k-th user at the m-th time instant, $w(n)$ represents sample of an AWGN process with variance $\sigma^2 = N_0/2$. We assume the channel coefficients h_k are perfectly known at the receiver [30]. After FFT operation, the received signal in the frequency domain is

$$\begin{aligned} R(n) &= \sum_{m=0}^{N-1} r(m) e^{-j2\pi nm/N} \\ &= \sum_{k=1}^{K} A_n H_k(n) x_k(n) + W(n), \end{aligned} \tag{3}$$

where $H_k(n)$ represents the frequency domain impulse response for the n-th symbol of the k-th user. $W(n)$ represents AWGN in frequency domain. In order to detect the signal of the k-th user, (3) can be rewritten as

$$\begin{aligned} R(n) &= A_n H_k(n) x_k(n) + \sum_{k' \neq k} A_n H_{k'}(n) x_{k'}(n) + W(n) \\ &= A_n H_k(n) x_k(n) + \zeta_k(n), \end{aligned} \tag{4}$$

where ζ_k represents the interference from channel and other $K-1$ users.

C. ITERATIVE DETECTION ALGORITHM OF TDCS-IDMA SYSTEM

The main function of ESE is to estimate the soft information of all users by considering the MAI between different users regardless of encoding constraints. Define the priori logarithm likelihood ratio (priori LLR) of $\{x_k(n), \forall k, n\}$ as

$$L_{priori}\left(x_k(n)\right) = \ln\left(\frac{\Pr\left(x_k(n) = +1\right)}{\Pr\left(x_k(n) = -1\right)}\right). \tag{5}$$

Then, the extrinsic log-likelihood ratios (LLRs) of ESE estimator are defined as [11]

$$e_{ESE}\left(x_k(n)\right) = \ln\left(\frac{p\left(r(n)|\, x_k(n) = +1\right)}{p\left(r(n)|\, x_k(n) = -1\right)}\right). \tag{6}$$

From the equation above, in order to calculate the extrinsic information, ESE needs to calculate the conditional probability density function. For the k-th user, the time domain received signal can be rewritten as

$$\begin{aligned} r(n) &= h_k x_k(n) + \sum_{k' \neq k} h_{k'} x_{k'}(n) + w(n) \\ &= h_k x_k(n) + \zeta_k(n), \end{aligned} \tag{7}$$

where $\zeta_k(n)$ is the distortion for the k-th user in time domain, including interference from others and noise.

Assume $x_k(n)$ is independent identically distributed random variables. According to the central-limit theorem, the second term $\zeta_k(n)$ can be approximated as a Gaussian variable, with a mean function $E\left(\zeta_k(n)\right)$ and variance function $Var\left(\zeta_k(n)\right)$, respectively. Therefore, the output of ESE for the k-th user is [11], [29]

$$e_{ESE}\left(x_k(n)\right) = 2h_k \frac{r(n) - E\left(\zeta_k(n)\right)}{Var\left(\zeta_k(n)\right)}. \tag{8}$$

In order to calculate $E(\zeta_k(n))$ and $Var(\zeta_k(n))$, the mean and variance functions of $x_k(n)$ are considered. The mean function is

$$\begin{aligned} E\left(x_k(n)\right) &= \sum_{x_k(n) \in \{+1,-1\}} x_k(n) \Pr\left(x_k(n)\right) \\ &= \Pr\left(x_k(n) = +1\right) - \Pr\left(x_k(n) = -1\right). \end{aligned} \tag{9}$$

According to (5), we have

$$\begin{cases} \Pr\left(x_k(n) = +1\right) = \dfrac{\exp\left(L_{priori}\left(x_k(n)\right)\right)}{\exp\left(L_{priori}\left(x_k(n)\right)\right) + 1} \\ \Pr\left(x_k(n) = -1\right) = \dfrac{1}{\exp\left(L_{priori}\left(x_k(n)\right)\right) + 1}. \end{cases} \tag{10}$$

By putting (10) into (9), the mean function is rewritten as

$$E\left(x_k(n)\right) = \tanh\left(\frac{L_{priori}\left(x_k(n)\right)}{2}\right). \tag{11}$$

The variance function can be calculated by the mean function. Therefore, the mean and variance functions of interference term $\zeta_k(j)$ are expressed as

$$\begin{aligned} E(\zeta_k(n)) &= E(r(n)) - h_k E(x_k(n)), \\ Var(\zeta_k(n)) &= Var(r(n)) - |h_k|^2 Var(x_k(n)). \end{aligned} \tag{12}$$

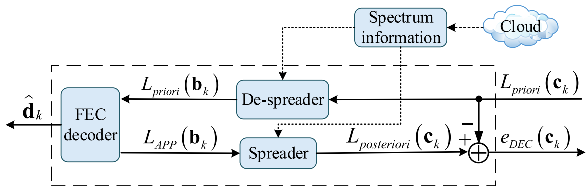

FIGURE 4. The DEC structure of TDCS-IDMA with BPSK modulation.

where $E(r(n))$ and $Var(r(n))$ are the mean and variance functions of the received signal, respectively.

Therefore, the ESE detection algorithm based on the theoretic analysis is given below under the assumption that the priori statistics $E(x_k(n))$ and $Var(x_k(n))$ are initialized [29]:

(1) Estimate the mean and variance functions of all users

$$\begin{aligned} E\left(x_k(n)\right) &= \tanh\left(L_{priori}\left(x_k(n)\right)/2\right), \\ Var\left(x_k(n)\right) &= 1 - \left(E\left(x_k(n)\right)\right)^2. \end{aligned} \tag{13}$$

(2) Calculate the mean and variance functions of the received signal

$$\begin{aligned} E(r(n)) &= \sum_{k=1}^{K} h_k E(x_k(n)), \\ Var(r(n)) &= \sum_{k=1}^{K} |h_k|^2 Var(x_k(n)) + \sigma^2. \end{aligned} \tag{14}$$

(3) Estimate the mean and variance functions of interference signal

$$\begin{aligned} E(\zeta_k(n)) &= E(r(n)) - h_k E(x_k(n)), \\ Var(\zeta_k(n)) &= Var(r(n)) - |h_k|^2 Var(x_k(n)). \end{aligned} \tag{15}$$

(4) Calculate the LLR outputs of ESE for the k-th user

$$e_{ESE}\left(x_k(n)\right) = 2h_k \frac{r(n) - E\left(\zeta_k(n)\right)}{Var\left(\zeta_k(n)\right)}. \tag{16}$$

The DEC of the receiver carries out a posterior probability (APP) decoding by using the output of ESE as input. It includes de-spreader, FEC decoder and spreader. DEC de-interleaves the extrinsic information output by ESE module to obtain prior information of DEC. Decoder then generates the corresponding external information, which is interleaved back to the ESE as prior information to update the mean and variance of the noise. The receiver gets the spectrum sensing results from cloud database and determines spectrum marking vector $\mathbf{B}$, so the interleave and spread procedures need to skip invalid subcarriers. Since every user uses exactly the same encoder and spreader, we can just consider the DEC for the k-th user, as shown in Fig. 4.

For convenience, taking the decoding process of the first encoded symbol $b_k(1)$ as an example, and the processes for other encoded symbols are the same. The DEC carries out the following operations:

(1) Obtain the soft estimator of b_k (1) based on the output of ESE

$$L_{priori}\left(b_k\left(1\right)\right) = \sum_{n=1}^{S} s\left(n\right) L_{priori}\left(c_k\left(n\right)\right), \quad (17)$$

where $\mathbf{s}$ is the spreading sequence.

(2) Perform standard APP decoding for FEC by using $L_{priori}\left(\mathbf{b}_k\right)$ as input, and generate the posteriori LLR $L_{APP}\left(\mathbf{b}_k\right)$ for $\mathbf{b}_k$.

(3) Obtain the posterior soft information of $\mathbf{c}_k$

$$L_{posteriori}\left(c_k(n)\right) = s_k(n)L_{APP}\left(b_k(1)\right), \quad n = 1, 2, \ldots, S. \quad (18)$$

(4) Calculate the external information of DEC output

$$e_{DEC}\left(c_k\left(n\right)\right) = L_{posteriori}\left(c_k\left(n\right)\right) - L_{priori}\left(c_k\left(n\right)\right). \quad (19)$$

In the process of iterative detection, the outputs of DEC decoders for all users feedback to ESE. If the receiver achieves a pre-set number of iterative detections, decoder calculates the LLR of data ($L_{APP}\left(\mathbf{d}_k\right)$) and outputs estimated data $\widehat{\mathbf{d}}_k$ by hard-decision decoding.

This scheme is also applicable to other modulation schemes such as QPSK and QAM, but the receiver need to be slightly adjusted.

III. TDCS-IDMA SYSTEM WITH CCSK MODULATION

TDCS-IDMA system with BPSK modulation can avoid occupied spectral bins and make full use of the interference generated by other users. However, traditional IDMA and TDCS-IDMA with BPSK modulation have similar disadvantages. Their performance degrades rapidly when the number of users is increased to be two times of the length of spreading code and significantly more iterations are needed to suppress MAI. To solve this problem, a new system framework based on CCSK is proposed in this paper. Users and subcarriers are divided into groups and each group's data are only transmitted on some subcarriers. CCSK modulation is applied to IDMA system to increase user capacity. In what follows, transmitter and receiver models are introduced and iterative detection algorithm is deduced.

A. TRANSMITTER STRUCTURE OF TDCS-IDMA SYSTEM WITH CCSK MODULATION

The transmitter structure of uplink TDCS-IDMA system with CCSK modulation is given in Fig. 5, which consists of four modules: CCSK modulator, spreader, interleaver and OFDM modulator.

CCSK is a form of M-ary signaling over a communication channel. In its simplest form, a fundamental modulation waveform (FMW) is chosen, and a cyclically (circularly) shifted version of the fundamental waveform is used to modulate a carrier [31], [32]. When M-ary CCSK is adopted, a sequence with a good cycle autocorrelation property $\mathbf{S}_0$ is chosen as the fundamental waveform. Then the data information can be expressed as $\mathbf{S}_0$ and its cyclic shift sequences are

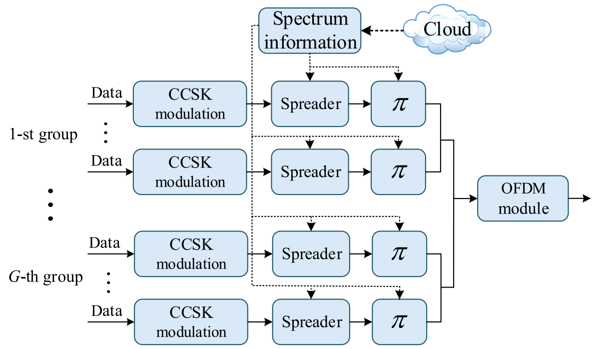

FIGURE 5. Block diagram of transmitter for TDCS-IDMA system with CCSK modulation.

$[\mathbf{S}_1, \mathbf{S}_2, \cdots, \mathbf{S}_k, \cdots, \mathbf{S}_{M-1}]$. In most cases, the fundamental waveform we consider here is a binary sequence $\mathbf{S}_0 = [b_0, b_1, \cdots, b_{M-1}]$, where $b_m = \pm 1$. Then its cyclic shift sequences can be written as

$$\mathbf{S}_{M-1} = [b_{M-1}, b_0, \cdots, b_{M-2}], \quad (20)$$

The function set $[b_0, b_1, \cdots, b_{M-1}]$ contains M elements to represent up to $\log_2(M)$ bits of data.

The first step at the transmitter is to get spectrum sensing results from cloud database. The number of available spectrum bins is N, and they are divided into G sub-channels, each of which contains N/G subcarriers. Therefore, each sub-channel is shared by $k_g = K/G$ users, and each user only occupies one sub-channel. For the k-th user, transmitting data $\mathbf{b}_k$ is modulated by CCSK modulation firstly, where the m sequence is chosen as the fundamental waveform of CCSK, and "-1" is used in the sequence instead of "0". After the CCSK modulation, other operations in the transmitter are the same as TDCS-IDMA with BPSK modulation. Specially, interleaver of each user in the same sub-channels must be different, so the correlation of sequence can be reduced to improve communication performance. However, k_g groups of users for different sub-channel can adopt the same independent random interleaver. Finally, OFDM transmission method is used for the resistance to frequency selective fading and ISI.

B. RECEIVER STRUCTURE OF TDCS-IDMA SYSTEM WITH CCSK MODULATION

The receiver structure of TDCS-IDMA system with CCSK modulation is given in Fig. 6. Except for the CCSK demodulation, other parts of receiver are consistent with TDCS-IDMA system with BPSK modulation. Because the signal of k-th user only exists in the corresponding sub-channel, signals from different groups could be separated by different sub-channels. Therefore, after getting spectrum information from cloud database, removing CP and FFT operation in the receiver, the k-th user only captures the information in the specific sub-channel. Furthermore, the computational complexity of multiuser IDMA system has a linear relationship with the number of users. The number of users for each sub-channel reduces as $1/G$ times of total number

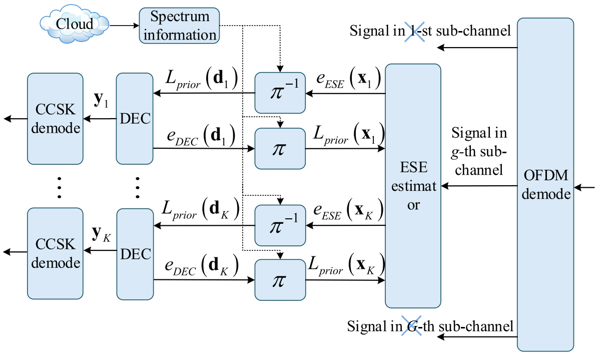

FIGURE 6. Block diagram of receiver for TDCS-IDMA system with CCSK modulation.

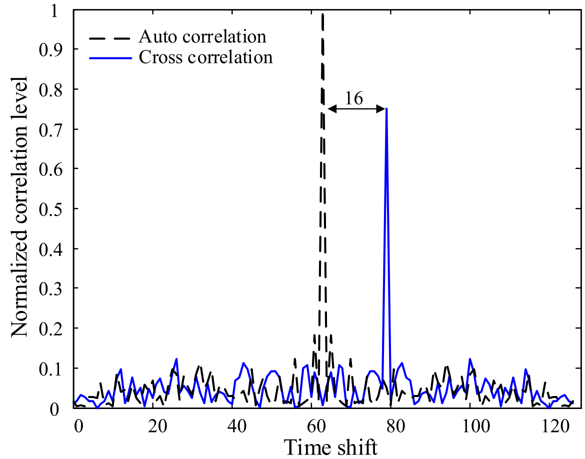

FIGURE 7. Correlation result of different sequences.

of users after grouping process. As a result, in terms of the number of users, the complexity of multiuser detection of each sub-channel for TDCS-IDMA with CCSK modulation is only $1/G$ times of original IDMA system.

For the purpose of simplifying hardware implementation, the current CCSK demodulation module mainly adopts a frequency domain method. Defining the received signal of n-th pulse shape is $\mathbf{r}(t) = \mathbf{S}_m(t)$, local reference sequence is $\mathbf{S}_0(t)$, where m is the cyclic shift value. Thus the output signal of correlator is expressed as

$$y(t) = \left| \int_{-\infty}^{\infty} \mathbf{r}(\tau) \mathbf{S}_0(\tau - t) \, d\tau \right|. \tag{21}$$

According to Wiener-Khinchin theorem, the Fourier transform has the following expression

$$Y(\omega) = \left| \mathbf{R}(\omega) \cdot \mathbf{S}_0^*(\omega) \right|. \tag{22}$$

In practical hardware processing, IFFT/FFT operation is commonly used to realize Fourier transform

$$\mathbf{y} = \left| IFFT \left\{ FFT(\mathbf{r}) \cdot FFT^* \{\mathbf{S}_0\} \right\} \right|. \tag{23}$$

Based on the operation, the correction calculation in time domain is transformed to multiplication operation in frequency domain, which greatly reduces the complexity in hardware implementation. After that, the output vector is $\mathbf{y} = [y_0, y_1, \cdots, y_{M-1}]$ and the estimated cyclic shift value of n-th pulse shape can be obtained by finding $\max(\mathbf{y}) = y_m$. Then the transmitting data is estimated through the hexadecimal conversion.

Assume the fundamental sequence is an m-sequence $\mathbf{a}$ with a length of 64, the modulated sequence $\mathbf{b}$ is generated by shifting $\mathbf{a}$ cyclically to the left by 16 places. Fig. 7 shows the auto and cross correlation results for different sequences. It is seen that the auto correlation function, i.e., the dotted curve, of the fundamental sequence has a peak magnitude in the figure, which means sequence $\mathbf{a}$ has good auto correlation property. The curve of solid line indicates the cross correlation function between fundamental sequence $\mathbf{a}$ and modulated sequence $\mathbf{b}$. Compared with the auto correlation function of $\mathbf{a}$, the position of correlation peak moves 16 places, and the distance between two peaks is the cyclic shift value of CCSK modulation.

The position of correlation peak can be calculated by the following operations

$$\begin{aligned} \mathbf{e}_1 &= \left| IFFT \left\{ FFT(\mathbf{b}) \cdot FFT^* \{\mathbf{a}\} \right\} \right|, \quad p_1 = \max_i, \mathbf{e}_1(i), \\ \mathbf{e}_2 &= \left| IFFT \left\{ FFT(\mathbf{a}) \cdot FFT^* \{\mathbf{a}\} \right\} \right|, \quad p_2 = \max_j, \mathbf{e}_2(j). \end{aligned} \tag{24}$$

The estimated transmitting data is $|p_1 - p_2|$.

IV. SIMULATION RESULTS

In CRNC, dynamic spectrum access technology can be used to avoid interference from authorized users and improve the capacity of system. In a distributed multiuser CR-OFDM system, users occupy disjoint spectrum resources dynamically, constituting a kind of dynamic frequency division multiple access system. Although the advantages of non-contiguous OFDM technology have been addressed in [22] and [23], a full consideration has not been given to adjacent interference among users and the channel fading factor. The transceiver structure based on IDMA is proposed in this paper. It has the ability to avoid occupied spectrum bins actively to make full use of the interference generated by other users. Thus better communication performance is to be achieved by iterative process.

A. THE NUMBER OF ITERATIONS FOR TDCS-IDMA WITH BPSK MODULATION

We mainly consider the effects of different number of iterations and users on multiple access TDCS-IDMA with BPSK modulation. Two cases of interference environment such as multi-tone interference and narrowband interference are taken into consideration. For further simplification, FEC coding is not considered in the simulation process. Specific simulation parameters are shown in Table. 1.

From the theoretical analysis above, the performance of multiuser TDCS-IDMA is closely related to the number of iterations. Generally, the higher the number of iterations is,

TABLE 1. Simulation parameters.

System	TDCS- IDMA systems, OFDM-IDMA system
Modulation type	BPSK, CCSK
Spreading code	{+1,-1}random sequence
Length of spreading code	16
Number of subcarrier	1024
Length of CP	32
Channel	AWGN channel, EVA channel

the heavier computational load and better communication performance are achieved. Therefore, the choice of the number of iterations should be compromised between the bit-error-rate (BER) performance and computational complexity. Let N_{Ite} be the number of iterations. Fig. 8 demonstrates the effects of the number of iterations on BER performance with 4 users in AWGN channel. Assume the spectrum marking vectors identified by spectrum sensing results from the transmitter and receiver are perfectly matched. It is easy to observe that the BER performance of proposed communication system can be improved with the increase of the number of iterations, and the curves for 4, 5, 6 iterations are almost overlapped. Considering the compromise between computational load and performance, let us choose 5 as the number of iterations for the subsequent simulations.

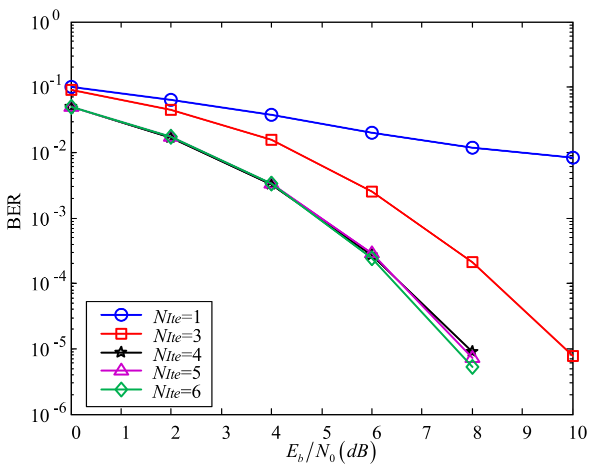

FIGURE 8. BER performance with different number of iterations of TDCS-IDMA with BPSK modulation.

B. DIFFERENT INTERFERENCE ENVIRONMENT FOR TDCS-IDMA WITH BPSK MODULATION

The spectrum sensing result in the case of multi-tone interference environment is provided in Fig. 9. It is observed that the element of spectrum marking vector is zero if the corresponding spectrum bin is occupied. Therefore, the proposed system framework can actively avoid interference spectrum bins. Fig. 10 shows simulation results of two systems in AWGN channel with different number of users in the case of multi-tone interference environment. Compared with TDCS-IDMA system with BPSK modulation, traditional OFDM-IDMA loses its robustness under multi-tone

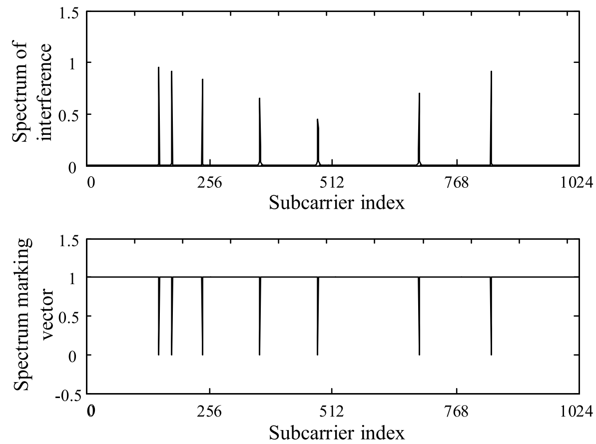

FIGURE 9. Spectrum sensing result in the case of multi-tone interference.

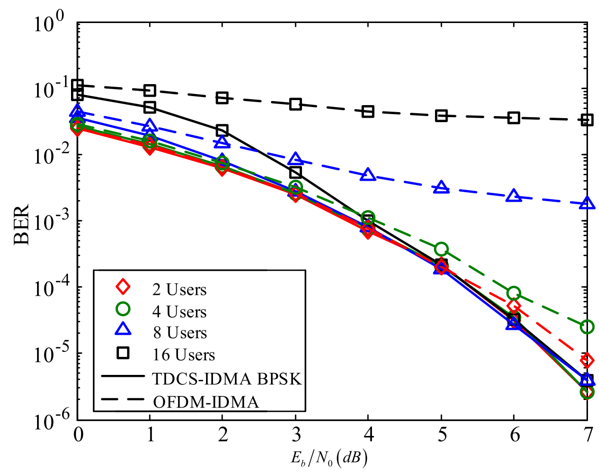

FIGURE 10. BER performance of TDCS-IDMA with BPSK modulation in the case of multi-tone interference.

interference, and the performance degrades rapidly when the number of users is larger than 8. Since the transmitting signal of each user avoids interference subcarriers actively in the proposed TDCS-IDMA system with BPSK modulation, the BER performances are quite close for different number of users, which confirms the viability of the proposed scheme. With lower signal-to-noise ratio (SNR), the performances for more users are slightly worse. This is because the superposition of noise increases so that the estimation of the interference from other users becomes inaccurate. It is seen that the performance of BER $= 10^{-2}$ at $E_b/N_0 \approx$ 1dB for $K = 4$, which corresponds to 2.5dB for $K = 16$. The curves for different number of users are consistent when SNR is high enough.

Fig. 11 and Fig. 12 illustrate the spectrum sensing results and BER performance with different number of users in the environment of two narrowband interference signals, respectively. As shown in Fig. 11, the spectrum marking vector is $\mathbf{A} = [\mathbf{1}_{N/4}, \mathbf{0}_{N/8}, \mathbf{1}_{N/4}, \mathbf{0}_{N/8}, \mathbf{1}_{N/4}]$, which means 25% spectrum bins are occupied. Other parameters are chosen

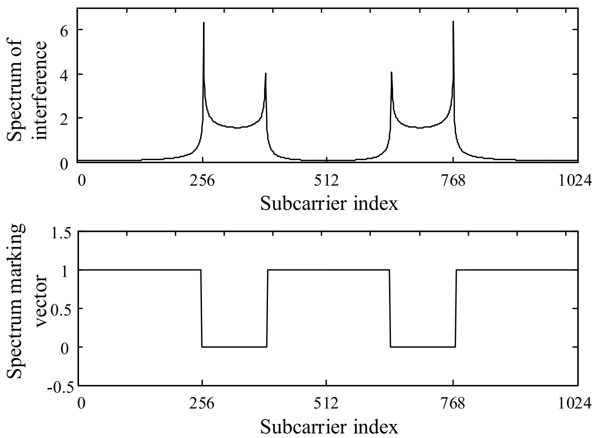

FIGURE 11. Spectrum sensing result with 25% subcarrier occupancy.

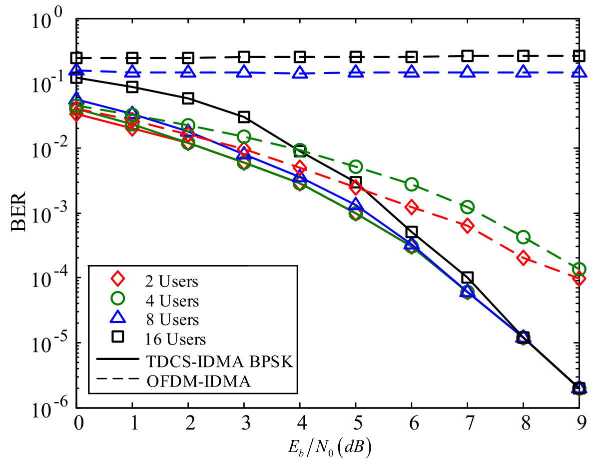

FIGURE 12. BER performance of TDCS-IDMA with BPSK modulation with 25% subcarrier occupancy.

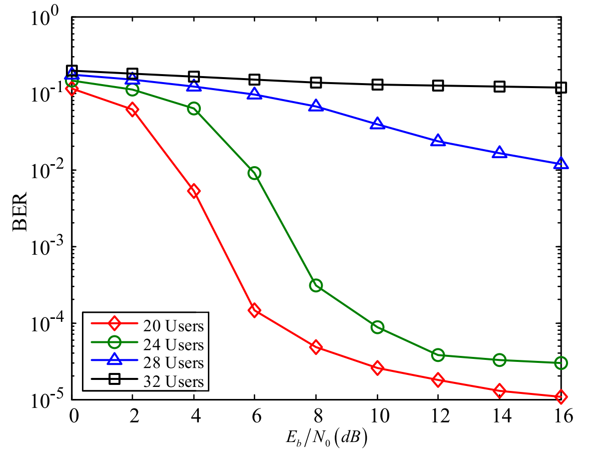

FIGURE 13. BER performance of different users for TDCS-IDMA with BPSK modulation.

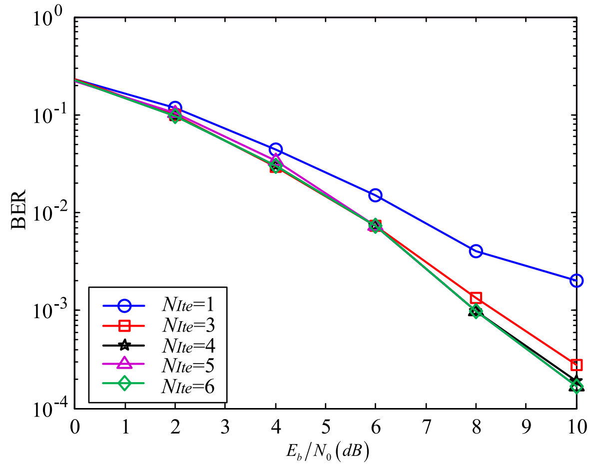

FIGURE 14. BER performance with different number of iterations of TDCS-IDMA with CCSK modulation.

as previously stated. Compared with Fig. 10, the multiuser communication performances of TDCS-IDMA with BPSK modulation in Fig. 12 have similar tendency, but curves are slightly worse. This is because occupied spectrum bins appear in the block. For example, the curves reach 10^{-5} at $E_b/N_0 \approx 6.5$dB when multi-tone interference exists, while the numerical value is greater than that of Fig. 12. The results of OFDM-IDMA are worse because of the expansion of interference spectrum bins, especially in the case of 8 and 16 users. Therefore, the proposed framework can work better than traditional OFDM-IDMA with spectral nulling.

Fig. 13 shows the BER performance of the proposed system when the number of users larger than the length of spreading code. It is observed that the communication performance degrades rapidly when the number of users is larger than the length of spread sequence and the system can hardly work when the number of users is twice the length of spreading code.

C. THE NUMBER OF ITERATIONS FOR TDCS-IDMA WITH CCSK MODULATION

In this section, simulations are performed to assess the communication performance of proposed TDCS-IDMA framework with CCSK modulation. Simulation parameters are: EVA channel and 64-ary CCSK modulation. Two groups are adopted to test and other parameters are the same as that of previous section. We also assume the state information of channel is perfectly known at the receiver, and localized subcarrier allocation (LSA) is used as the allocation algorithm of subcarrier, which has been widely applied in LTE standard [34].

Similarly, we first study the effect of number of iterations for TDCS-IDMA with CCSK modulation in EVA channel. The number of users is 4 and multi-tone interference environment (as Fig. 9 shown) is simulated. As shown in Fig. 14, the BER performance is improved with the increase of the number of iterations, and difference between different number of iterations is smaller compared with TDCS-IDMA with BPSK modulation. Compared with Fig. 8, CCSK modulation has worse performance than BPSK modulation since this simulation is performed under poorer channel conditions. It shows TDCS-IDMA with CCSK modulation can eliminate

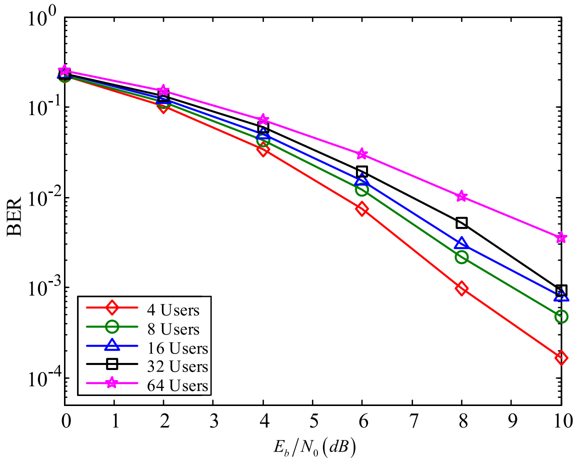

FIGURE 15. BER performance of TDCS-IDMA with CCSK modulation in the case of multi-tone interference.

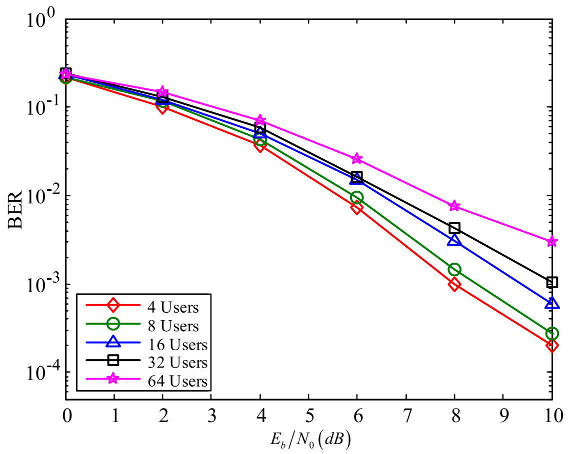

FIGURE 16. BER performance of TDCS-IDMA with CCSK modulation with 25% subcarrier occupancy.

interference with smaller number of iterations, which can greatly decrease the decoding complexity of the system. For the purpose of fair comparison, 5 iterations are chosen for the subsequent simulations.

D. PERFORMANCE UNDER DIFFERENT INTERFERENCE ENVIRONMENT FOR TDCS-IDMA WITH CCSK MODULATION

Fig. 15 and Fig. 16 show the simulation results in the case of multi-tone interference and two narrowband interference environment. The spectrum states are given in the subsection B. From these two figures, different number of users are tested. It is easily noticed that the proposed TDCS-IDMA with CCSK modulation has better BER performance with a larger number of users, which results from user grouping operation and CCSK modulation. In particular, when the number of users reaches two times of the length of spreading code, TDCS-IDMA with BPSK modulation can hardly work, while TDCS-IDMA with CCSK modulation still has certain advantages. This is because when the number of users is small, the additive noise is the main interference source, and its influence gradually reduces with the increase of SNR. When a large number of users are communicating simultaneously, the main interference source changes into multiple access interference, which is invariable with the change of SNR. Each sub-channel contains a smaller number of users to minimize the interference between users through the grouping operation. At the same time, CCSK modulation can obtain soft spread spectrum gain and enhance the user capacity of the system. Furthermore, the performances in the case of multi-tone interference and 25% subcarrier occupancy environment are basically consistent, which verifies the anti-interference ability of the proposed system. Therefore, better performance and larger user capacity are achieved by the improved system.

V. CONCLUSION

In this paper, we have presented a multiple access method for dynamic spectrum access in CRNC. The proposed method uses IDMA to make full use of all users' information, rather than simply treating them as interference. We have proposed two modulation types, BPSK and CCSK for TDCS-IDMA system. TDCS-IDMA with BPSK modulation can avoid the occupied spectrum bins, and obtain better performance compared with traditional OFDM-IDMA system. To further enhance user capacity and reduce decoding complexity, TDCS-IDMA with CCSK modulation was proposed. Simulation results are provided to demonstrate the feasibility and performance improvement of scheme proposed in the paper. Compared with traditional OFDM-IDMA system, a large performance improvement is obtained for the proposed systems under different cases of spectral nulling.

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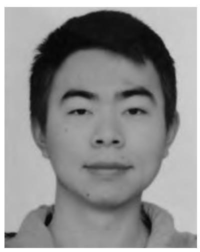

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