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Frequency-Domain Oversampling for Cognitive CDMA Systems: Enabling Robust and Massive Multiple Access for Internet of Things

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ABSTRACT Toward the era of mobile internet and Internet of Things (IoT), numerous sensors and devices are being introduced and interconnected. To support such amount of data traffic, traditional wireless communication technologies are facing challenges both in terms of increasingly shortage of spectrum resource and massive multiple access. In this paper, cognitive code division multiple access (Cognitive-CDMA) is proposed by combining the concept of cognitive radio with dynamic noncontinuous spectrum bands and code division multiple access. In order to suppress multiple access interference resulting from the non-orthogonality of partial available spectrum bins, carrier frequency offset, and spectrum sensing mismatch, an enhanced receiver design using frequency-domain oversampling (FDO) with linear minimum mean square error (MMSE) is considered in this paper for Cognitive-CDMA systems. By spectrum sensing to mitigate spectral interference in the transceiver and by utilizing FDO in the receiver to project received signal to a higher dimension, the proposed Cognitive-CDMA is able to support robust and massive multiple access for IoT applications. The simulation results show that the cognitive-CDMA with FDO-MMSE receiver outperforms that with conventional per-user MMSE receiver in the presence of multipath fading channels, carrier frequency offset, and spectrum sensing mismatch.

INDEX TERMS Internet of things, cognitive radio, code division multiple access, frequency-domain oversampling, multiple access.

I. INTRODUCTION

The fifth generation (5G) of wireless system is designed to fuel new communication paradigms, such as internet of things (IoT) and mobile internet services, where numerous sensors and devices are interconnected and demanded for improvements on several issues. The rapid development of IoT has trigger 1000-fold data traffic increase by 2020 for 5G, however it introduces a large of unexpected electromagnetic interference [1]. Therefore, investigating higher spectral efficiency technology becomes one of the key breakthrough. Meanwhile, due to the fast growth of IoT, 5G also needs to support massive access among users and/or devices. To address the issue, enhanced technologies are necessary.

So far, several potential candidates for 5G massive multiple access have been proposed, such as sparse code multiple access [2], narrowband internet of things [3], and MIMO-based multiple access [4], [5]. From the observation on these IoT supporting technologies, they generally require an entire continuous spectrum band to support their services. However till now, the shortage of spectrum resource becomes more serious, and it is difficult to find a continuous spectrum band with large bandwidth to support IoT applications. According to Shannon's capacity theorem, the larger spectrum resource can achieve the higher systematic capacity, even through noncontinuous spectrum bands. Motivated by this idea, as an alternative to existing methods, cognitive code division multiple access (Cognitive-CDMA) is proposed in this paper for IoT applications by combining the concept of cognitive radio (CR) with dynamic noncontinuous spectrum bands and code division multiple access (CDMA). By employing spectrum sensing and frequency-domain spreading, cognitive-CDMA systems allow users to interact with surrounding environment and transmit signal over clean and noncontinuous spectrum bands. The idea of cognitive-CDMA is oriented from transform domain communication systems (TDCS), which have been widely used as a CR overlay technology [6]–[10]. The basic idea behind TDCS aims to dynamically synthesis a smart waveform based on the knowledge of surrounding environment [11]–[14].

For the purpose of multiple access, a cognitive-CDMA system utilizes a set of pseudorandom polyphase sequences, which are generated from linear feedback shift register and polyphase mapping, for frequency-domain spreading. However in CR scenarios, since partial spectrum bins are occupied by other wireless communication systems, the orthogonality among spreading sequences is destroyed, leading to multiple access interference (MAI). In addition, channel uncertainties are likely to produce spectrum sensing mismatch between available spectrum bins obtained by both the transmitter and receiver, resulting in a significant rise of MAI [8], [15]. As a result, these two key problems become a bottleneck of practical cognitive-CDMA systems.

Quite recently, the concept of frequency-domain oversampling (FDO) technique with linear minimum mean square error (MMSE) principle has been proposed for multicarrier systems to effectively suppress MAI [16]–[18]. Motivated by the capability of MAI suppression, in this paper, cognitive-CDMA with FDO-MMSE receiver is considered by projecting received signals as well as original channel information into fractionally spaced frequency domain (FSFD) [19]. Following this method, more information behind channel transmission can be extracted. Moreover, spectrum sensing mismatch is a specific problem for cognitive-CDMA systems when compared to conventional other multiple access schemes. Thus, FDO-MMSE receiver is also utilized to deal with the effect of spectrum sensing mismatch. Simulation results validate that, cognitive-CDMA with FDO-MMSE receiver outperforms that with per-user MMSE (PU-MMSE) and is more robust against the effect of MAI, which mainly comes from multipath fading channels, carrier frequency offset and spectrum sensing mismatch.

This paper is organized as follows. Section II presents the system model of cognitive-CDMA systems and formulates the problem of MAI in case of spectrum sensing. In Section III, cognitive-CDMA with FDO-MMSE receiver is presented. In the end, numerical simulations are presented in Section IV, and this paper is summarized in Section V.

II. SYSTEM MODELS AND PROBLEM FORMULATIONS OF COGNITIVE-CDMA SYSTEMS

A. SYSTEM MODELS

In cognitive radio systems, the entire spectrum band is divided into N spectrum bins, and a spectrum availability

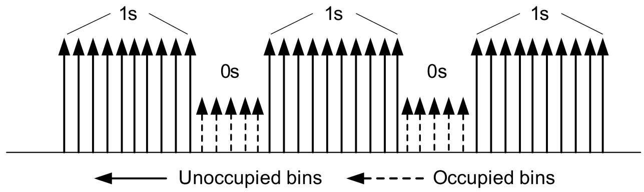

FIGURE 1. White/black space spectrum and spectrum availability vector A.

vector, $\mathbf{A} = [A_0, A_1, \ldots, A_{N-1}]$, is used to represent the distribution of spectrum holes. Note that the value of A_k is set to 1 (or 0) if the kth bin is unoccupied (or occupied), as shown in Fig. 1. We assume that there are N_C unoccupied bins inside the set Ω, i.e., $\{A_k = 1, k \in \Omega\}$, and the same spectrum marking vector is obtained by the spectrum sensing facilities on the receiver side.

On the transmitter side of cognitive-CDMA systems, a user-specific complex pseudorandom (PR) polyphase vector, $\mathbf{P} = \left[e^{jm_0}, e^{jm_1}, \ldots, e^{jm_{N-1}}\right]$, is multiplied element-by-element with spectrum availability vector, $\mathbf{A}$, to produce a spectral vector $\mathbf{B}$, i.e., $\mathbf{B} = \mathbf{P} \cdot diag\,(\mathbf{A})$. The fundamental modulation waveform (FMW), $\mathbf{b}$, is achieved by performing an IFFT operation,

$$\begin{aligned} \mathbf{b} &= [b_0, b_1, \ldots, b_{N-1}] \\ b_n &= \lambda \sum_{k=0}^{N-1} A_k e^{jm_k} e^{\frac{j2\pi kn}{N}} = \lambda \sum_{k\in\Omega} e^{jm_k} e^{\frac{j2\pi kn}{N}}, \end{aligned} \tag{1}$$

where $\lambda = \sqrt{N/N_C}$ is an energy normalization factor. Through a M-ary QAM modulator, the transmitted signal, $\mathbf{x} = [x_0, x_1, \ldots, x_{N-1}]$, based on the FMW is achieved as

$$x_n = \lambda S \sum_{k\in\Omega} e^{jm_k} e^{\frac{j2\pi kn}{N}}, \tag{2}$$

where S is the modulated M-ary QAM symbol.

On the receiver side, the received signal, $\mathbf{r} = [r_0, r_1, \ldots, r_{N-1}]$, is correlated with the local reference FMW to recover input data symbols by demodulating maximum correlation output. It should be note that, the local reference FMW on the receiver is highly dependent on spectrum available vector. Since the information on S is hidden in the background noise by spreading over all available spectrum bins, cognitive-CDMA signals have a low probability of being intercepted by unauthorized listeners.

B. PROBLEM FORMULATIONS

Let us consider a K-user cognitive-CDMA system in which each user is assigned a specific PR polyphase sequence to share available spectrum resources. Following the method in [11] for generating PR polyphase sequences, the class of polyphase sequences is given by

$$\begin{aligned} \mathbf{P} &= [\mathbf{P}_1, \mathbf{P}_2, \ldots, \mathbf{P}_K] \\ \mathbf{P}_i &= \left[e^{jm_0^i}, \ldots, e^{jm_k^i}, \ldots, e^{jm_{N-1}^i}\right], \end{aligned} \tag{3}$$

where $\mathbf{P}_i$ denotes the PR sequence for the ith user and $e^{jm_k^i}$ denotes the kth sequence element of $\mathbf{P}_i$. Based on (1), a class of FMWs assigned to multiple users is given by

$$\mathbf{b} = [\mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_K]$$
$$\mathbf{b}_i = \left[b_0^i, b_1^i, \ldots, b_{N-1}^i\right]$$
$$b_n^i = \lambda \sum_{k\in\Omega} e^{jm_k^i} e^{\frac{j2\pi kn}{N}}. \tag{4}$$

From previously reported results in [7], we define the cross-correlation function between any pair of FMWs (i, j) as follows,

$$\varphi_{\mathbf{b}_i,\mathbf{b}_j}(\tau) = \sum_{n=0}^{N-1} b_n^i \left(b_{n+\tau}^j\right)^* \neq 0, \forall\tau, \tag{5}$$

where $(\cdot)^*$ denotes the complex conjugate. As shown in Fig. 2, the orthogonality among spreading sequences cannot be obtained even Walsh-Hadamard sequences are used for cognitive-CDMA systems. This is because traditional sequence design generally assumes the availability of entire spectrum band (rather than certain noncontinuous spectrum bands in a CR system as specified by the spectrum hole constraint) for every sequence. The orthogonal property of Walsh-Hadamard sequences will be damaged if a spectrum hole constraint is imposed by spectral nulling. Hence, MAI always exists in cognitive-CDMA systems, leading to significant BER performance degradation.

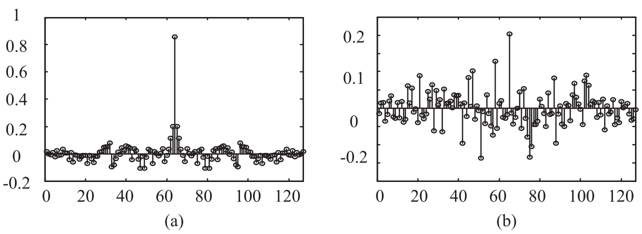

FIGURE 2. Correlation properties of imperfect user spreading sequences in cognitive-CDMA systems.

Meanwhile, in cognitive radio systems, channel uncertainties are likely to produce spectrum sensing mismatch between available spectrum bins obtained by the transmitter and receiver respectively, as shown in Fig. 3. Here, three sets of available spectrum bins with respect to spectrum sensing results are expressed,

- $\mathbf{A}^{Tx} = \left[A_0^{Tx}, A_1^{Tx}, \ldots, A_{N-1}^{Tx}\right]$, where $\{A_k^{Tx} = 1, k \in \Omega_{Tx}\}$ for available bins by spectrum sensing at the transmitter, with $\|\Omega_{Tx}\| = N_{Tx}$.
- $\mathbf{A}^{Rx} = \left[A_0^{Rx}, A_1^{Rx}, \ldots, A_{N-1}^{Rx}\right]$, where $\{A_k^{Rx} = 1, k \in \Omega_{Rx}\}$ for available bins by spectrum sensing at the receiver, with $\|\Omega_{Rx}\| = N_{Rx}$.
- $\mathbf{A}^{TR} = \left[A_0^{TR}, A_1^{TR}, \ldots, A_{N-1}^{TR}\right]$, where $\{A_k^{TR} = 1, k \in \Omega_{TR}\}$ for available bins at both the transmitter and the receiver, with $\Omega_{TR} = \Omega_{Tx} \bigcap \Omega_{Rx}$ and $\|\Omega_{TR}\| = N_{TR}$.

In this paper, a mismatch factor with respect to spectrum sensing mismatch is defined as [15]:

$$\alpha = 1 - \frac{(N_{TR})^2}{N_{Tx}N_{Rx}} \leq 1 \tag{6}$$

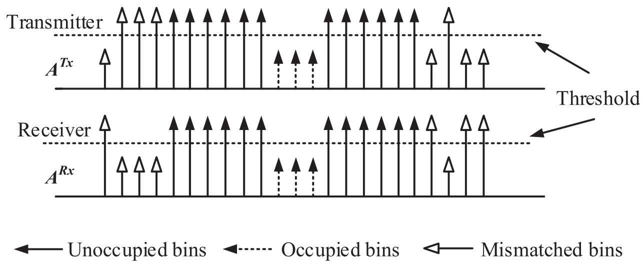

FIGURE 3. Example of spectrum sensing mismatch for cognitive-CDMA systems.

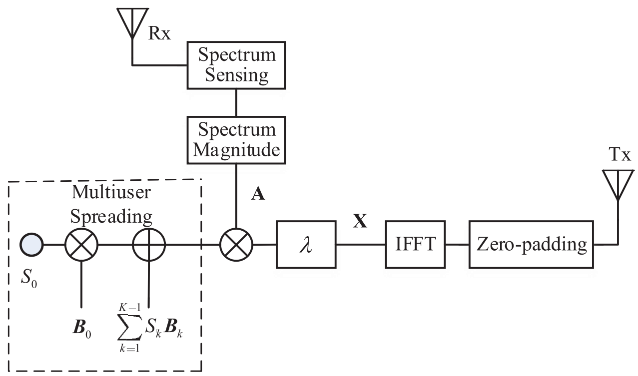

FIGURE 4. Block diagram of the cognitive-CDMA transmitter.

III. FREQUENCY-DOMAIN OVERSAMPLING FOR COGNITIVE-CDMA SYSTEMS

In this paper, a practical cognitive-CDMA system is proposed to deal with the effect of MAI and spectrum sensing mismatch. Let us consider a K-user cognitive-CDMA system and focus on only one transmission block. As shown in Fig. 4, inter-block interference is eliminated by using the zero-padding postfix. The length of ZP, i.e., N_{GI}, should be larger than the maximum channel delay spread, and the length of one transmission block is $P = N + N_{GI}$. Recalling from (2) (3), the transmitted signal of the kth cognitive-CDMA user over $[0, P]$ can be expressed as

$$x_n^k = \begin{cases} \lambda S_k \sum\limits_{k\in\Omega_{Tx}} e^{jm_k^i} e^{\frac{j2\pi kn}{N}}, & (n = 0, 1, \ldots, N-1) \\ 0, \quad (n = N, N+1, \ldots, N+N_{GI}-1) \end{cases} \tag{7}$$

where S_k is the modulated M-ary QAM symbol for the kth user. It should be note that, in cognitive-CDMA systems, one common spectrum availability vector, i.e., $\mathbf{A}^{Tx} = \left[A_0^{Tx}, A_1^{Tx}, \ldots, A_{N-1}^{Tx}\right]$, is shared among all users at transmitter sides, and each user adopt a distinct PR polyphase vector for phase coding to accomplish multiple access capability.

The downlink transmitted signal in (7) is expressed in matrix as

$$\mathbf{x} = \begin{cases} \lambda \mathbf{F}_{N\times N}^H \mathbf{B}^{Tx}\mathbf{S}, & (n = 0, 1, \ldots, N-1) \\ \mathbf{0}, & (n = N, \ldots, N+N_{GI}-1) \end{cases} \tag{8}$$

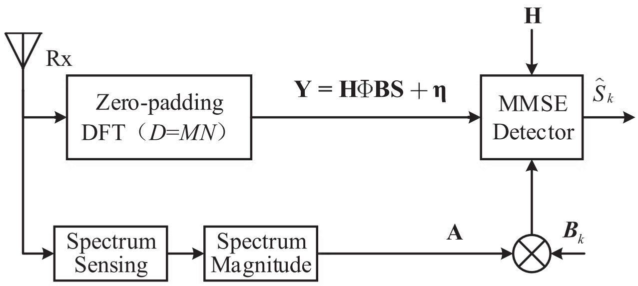

FIGURE 5. Block diagram of the FDO-based cognitive-CDMA receiver.

where $\mathbf{S} = [S_1, S_2, \ldots, S_K]^T$ refers to information over different user symbols, $\mathbf{B}^{Tx}$ is the spreading code matrix as

$$\begin{aligned}\mathbf{B}^{Tx} &= \left[\mathbf{B}_0^{Tx}, \mathbf{B}_1^{Tx}, \ldots \mathbf{B}_{K-1}^{Tx}\right] \\ \mathbf{B}_k^{Tx} &= \mathbf{P}_k \cdot diag\left(\mathbf{A}^{Tx}\right), k = 1, 2, \ldots, K, \end{aligned} \tag{9}$$

and the discrete Fourier transform (DFT) matrix as

$$\begin{aligned}\mathbf{F}_{N\times N} &= \left[\frac{1}{\sqrt{N}} \exp\left(-j\frac{2\pi}{N}np\right)\right]_{N\times N}, \\ &\qquad (n, p = 0, 1, \ldots, N-1). \end{aligned} \tag{10}$$

Furthermore, (8) can be rewritten as

$$\mathbf{x} = \Xi_{GI}\mathbf{F}_{N\times N}^{H}\mathbf{B}^{Tx}\mathbf{S}, \tag{11}$$

where

$$\Xi_{GI} = \left[\mathbf{I}_{N\times N}^{T}\ \mathbf{0}_{N_{GI}\times N}^{T}\right]^T. \tag{12}$$

In this paper, a well-accepted quasi-static multipath fading channel is adopted, and the impulse response is

$$h(\tau) = \sum_{l}^{L-1} h_l \delta(\tau - \tau_l), \quad \sum_{l}^{L-1} \mathbb{E}\left[h_l h_l^*\right] = 1 \tag{13}$$

where L is the number of paths in total, $\{\tau_l\}_{l=0}^{L-1}$ denote delays and $\{h_l\}_{l=0}^{L-1}$ denote path gains. For the receiver shown in Fig. 5, the discrete received signal, $\mathbf{r}$, of length $P = N + N_{GI}$ is first obtained. And then, $\mathbf{r}$ is zero-padded to the length of $D = MN$ for the purpose of frequency-domain oversampling (FDO). Here, a FDO factor, M, is applied to transform the received signal back to frequency-domain for projecting the received signal into fractional spaced frequency domain (FSFD), with new subcarrier spaced at $f = \frac{1}{T}\left(\frac{d}{M} + \varepsilon\right)$, where $d = 0, 1, \ldots, D-1$, and ε models the effect of frequency offset. Note that M doesn't necessarily be an integer.

When passing through multipath fading channels, the received signal after zero-padding operation can be written as [17]

$$\begin{aligned}\mathbf{r} &= \mathbf{O}(\varepsilon)\, \Xi_{ZP}\mathbf{h}_{GI}\mathbf{x} + \Xi_{ZP}\mathbf{z} \\ &= \Xi_{ZP}\mathbf{h}_{GI}\,\Xi_{GI}\mathbf{F}_{N\times N}^{H}\mathbf{B}^{Tx}\mathbf{S} + \Xi_{ZP}\mathbf{z} \end{aligned} \tag{14}$$

where $\Xi_{ZP} = \left[\mathbf{I}_{P\times P}^{T}\ \mathbf{0}_{(D-P)\times P}^{T}\right]^T$ denotes the zero-padding operation in the receiver, $\mathbf{h}_{GI}$ is a lower triangular Toeplitz matrix with the first column, $[h_0, h_1, \ldots, h_{L-1}, 0, \ldots, 0]^T$, and

$$\mathbf{O}(\varepsilon) = diag\left(1, e^{-j\frac{2\pi}{N}\varepsilon}, \ldots, e^{-j\frac{2\pi}{N}(D-1)\varepsilon}\right), \tag{15}$$

and $\mathbf{z}$ denotes additive white Gaussian noise vector with variance σ_n^2. According to the principle of discrete Fourier transform, the equivalent overall channel matrix can be model as [17]

$$\Xi_{ZP}\mathbf{h}_{GI}\,\Xi_{GI} = \mathbf{F}_{D\times D}^{H}\widetilde{\mathbf{H}}\mathbf{F}_{D\times N}, \tag{16}$$

where

$$\begin{aligned}\mathbf{F}_{D\times D} &= \left[\frac{1}{\sqrt{N}} \exp\left(-j\frac{2\pi}{N}np\right)\right]_{D\times D}, \\ &\qquad (n, p = 0, 1, \ldots, D-1), \\ \mathbf{F}_{D\times N} &= \left[\frac{1}{\sqrt{N}} \exp(-j\frac{2\pi}{N}\frac{d}{M}p)\right]_{D\times N}, \\ &\qquad (p = 0, \ldots, N-1; d = 0, \ldots, D-1), \end{aligned} \tag{17}$$

and the channel frequency response with FDO can be written as

$$\begin{aligned}\widetilde{\mathbf{H}} &= \left[diag\left(\widetilde{H}_0, \widetilde{H}_1, \ldots, \widetilde{H}_d, \ldots \widetilde{H}_{D-1}\right)\right]_{D\times D} \\ \widetilde{H}_d &= \sum_{l=0}^{L-1} h_l e^{-j2\pi d\tau_l/N}, \quad d = 0, 1, \ldots, D-1. \end{aligned} \tag{18}$$

Thus, the received signal can be rewritten as

$$\begin{aligned}\mathbf{r} &= \mathbf{O}(\varepsilon)\,\mathbf{F}_{D\times D}^{H}\widetilde{\mathbf{H}}\mathbf{F}_{D\times N}\mathbf{F}_{N\times N}^{H}\mathbf{B}^{Tx}\mathbf{S} + \Xi_{ZP}\mathbf{z} \\ &= \mathbf{F}_{D\times D}^{H}\widetilde{\mathbf{H}}\Phi\mathbf{B}^{Tx}\mathbf{S} + \Xi_{ZP}\mathbf{z}, \end{aligned} \tag{19}$$

where

$$\Phi = \mathbf{F}_{D\times N}\mathbf{O}(\varepsilon)\,\mathbf{F}_{N\times N}^{H}. \tag{20}$$

Similarly, the received signal $\mathbf{r}$ in the FSFD is given by

$$\widetilde{\mathbf{Y}} = \mathbf{F}_{D\times D}\mathbf{r} = \widetilde{\mathbf{H}}\Phi\mathbf{B}^{Tx}\mathbf{S} + \boldsymbol{\eta}. \tag{21}$$

Note that the signal term now becomes a colored zero-mean Gaussian noise vector because of FDO operation,

$$\mathbb{E}\left[\boldsymbol{\eta}\boldsymbol{\eta}^H\right] = \frac{N_0}{K}\boldsymbol{\Gamma}, \quad \boldsymbol{\Gamma} = \mathbf{F}_{D\times P}\mathbf{F}_{D\times P}^{H}. \tag{22}$$

For a traditional linear MMSE detector, the transmitted user symbol can be estimated by multiplying an optimal weight matrix to the frequency domain signal, i.e., $\widehat{S}_k = \widetilde{\mathbf{w}}_k^H\widetilde{\mathbf{Y}}$. Here, the weight matrix for each user, $\widetilde{\mathbf{w}}_k$, is the key design parameter and depends on performance criteria used. The idea of FDO-MMSE receiver design is to firstly project those input signals needed for $\widetilde{\mathbf{w}}_k$ to the FSFD, which contains more information about the operation of signal passing multipath fading channels.

It should be note that, in present of spectrum sensing mismatch, the spectrum availability vector $\mathbf{A}^{Rx}$ in the receiver is different from that in the transmitter $\mathbf{A}^{Tx}$, leading to FMWs in transceiver sides being different. On the receiver side, $\mathbf{B}^{Rx}$ denotes the local reference spreading code matrix as

$$\begin{aligned}\mathbf{B}^{Rx} &= \left[\mathbf{B}_0^{Rx}, \mathbf{B}_1^{Rx}, \ldots \mathbf{B}_{K-1}^{Rx}\right] \\ \mathbf{B}_k^{Rx} &= \mathbf{P}_k \cdot diag\left(\mathbf{A}^{Rx}\right), \quad k = 1, 2, \ldots, K. \end{aligned} \tag{23}$$

In this paper, Bayesian Gauss-Markov theorem is applied to derive the FDO-MMSE receiver weight matrix,

$$\begin{aligned}\widetilde{\mathbf{w}}_k &= \mathbb{E}\left[\widetilde{\mathbf{Y}}\widetilde{\mathbf{Y}}^H\right]^{\dagger}\mathbb{E}\left[\widetilde{\mathbf{Y}}S_k\right] \\ &= \left(\widetilde{\mathbf{H}}\Phi\mathbf{P}diag\left(\mathbf{A}^{Tx}\right)\mathbf{P}^H\Phi^H\widetilde{\mathbf{H}}^H + N_0\mathbf{\Gamma}\right)^{\dagger} \\ &\quad\times\left(\widetilde{\mathbf{H}}\Phi\mathbf{P}_k diag\left(\mathbf{A}^{Rx}\right)\right) \end{aligned} \tag{24}$$

Note that the Moore-Penrose pseudoinverse method is used since the oversampling operation results in a rank-deficient matrix. In addition, because of occupied spectrum bins and spectrum sensing mismatch, $\mathbf{P}diag\left(\mathbf{A}^{Tx}\right)\mathbf{P}^H \neq N \cdot \mathbf{I}_{N\times N}$, which introduce considerable MAI. Nevertheless, the effect of MAI can be significantly compensated by FDO-MMSE operation.

IV. SIMULATION RESULTS

In this paper, a downlink cognitive-CDMA system with $N = 64$ spectrum bins is considered. Unless otherwise specified, a multipath channel model of six paths is used. To perform zero-padding DFT in the receiver, a ZP of length $1/4$ is added in the transmitter as guard interval, and more zeros are added to the received signal. The padding length depends on the FDO factor M. System performances in terms of bit error rate (BER) with and without FDO are compared to per-user MMSE (PU-MMSE) detection methods. More simulation parameters can be found in the table 1.

TABLE 1. Simulation parameters for different multiuser cognitive-CDMA receivers.

Parameters	Symbols	FDO-MMSE	PU-MMSE
Users	K	32	32
Mismatch factor	α	0 / 25% / 50%	0 / 25% / 50%
Normalized CFO	ε	0/0.02/0.04/0.06	0/0.02/0.04/0.06
Oversampling factor	M	70/64	1

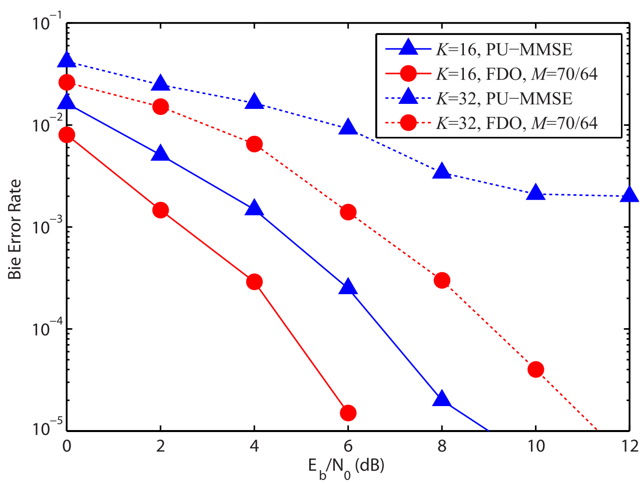

FIGURE 6. BER Performance comparison of different receivers in an ideal 6-path multipath fading channel.

We firstly investigate an ideal multipath channel where MAI is only introduced by multipath fading channels. As seen in Fig. 6, both in moderate loading ($K = 16$) and heavy loading ($K = 32$), the FDO-MMSE receiver outperforms traditional PU-MMSE receiver in terms of BER. Especially, when BER=10^{-4}, the FDO-MMSE receiver can obtain 2dB performance improvement in case of heavy loading. Meanwhile, a cognitive-CDMA system is intrinsically a multicarrier signaling, which requires the strict orthogonality among subcarriers and is therefore sensitive to CFO. Hence, BER performances of different MMSE receivers in present of CFO are shown in Fig. 7. Clearly, the PU-MMSE receiver shows bad BER performance due to inter-carrier interference from CFO. However for our proposed FDO-MMSE receiver, it achieves a comparable robust BER performance under the effect of both frequency selective fading channels and CFO.

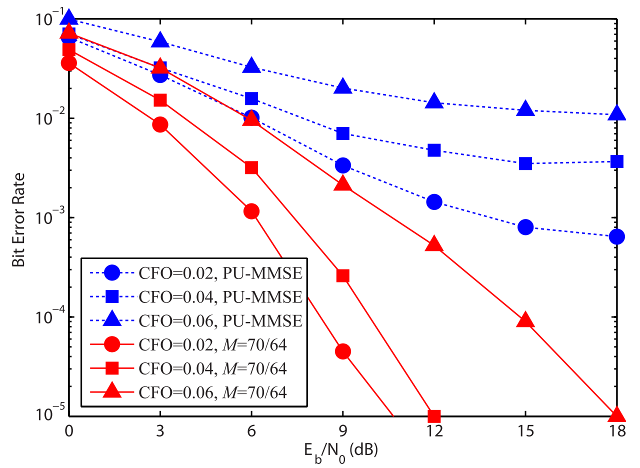

FIGURE 7. BER Performance comparison of different receivers in present of CFO.

Another MAI facing cognitive-CDMA systems is spectrum sensing. Cognitive-CDMA signal often transmit over noncontinuous spectrum bands, which may considerably destroy the orthogonality among user spreading sequences. As shown in Fig. 8, the FDO-MMSE receiver can tolerate

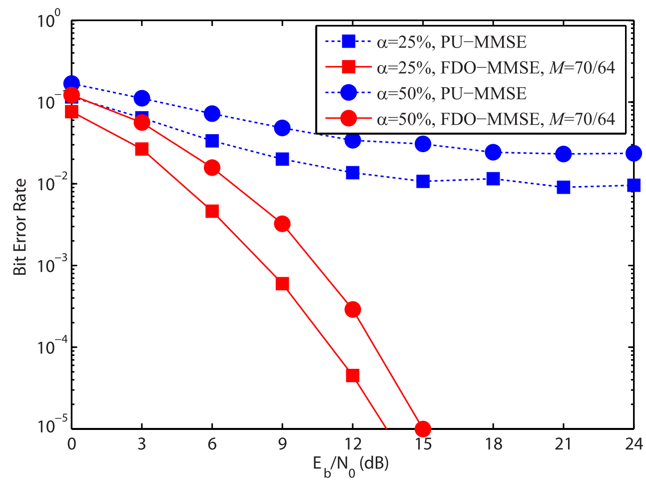

FIGURE 8. BER Performance comparison of different receivers in present of spectrum sensing mismatch.

serious spectrum sensing mismatch and reduce the effect of non-orthogonality among user spreading sequences. In addition, we also consider a six-path frequency selective fading channel with $\alpha = 25\%$ and CFO $\varepsilon = 0.02$. As shown in Fig. 9, simulation results show that the FDO-MMSE receiver success to maintain a more robust performance compared to the PU-MMSE receiver.

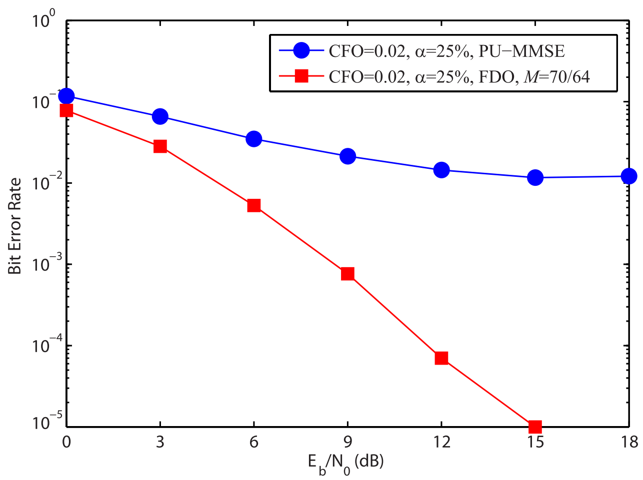

FIGURE 9. Performance comparison of FDO-MMSE receiver and PU-MMSE receiver in present of hybrid MAIs.

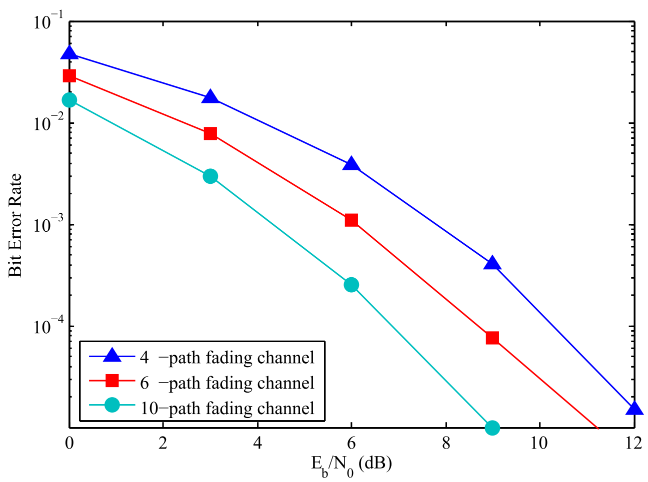

FIGURE 10. BER Performance comparison of FDO-MMSE receiver through different multipath fading channels.

Simulation results mentioned above demonstrate that, the FDO-MMSE receiver can fully utilize extra information exacted from frequency-domain oversampling process, and performance gain comes from multipath diversity, or equivalently, frequency diversity [20]. Fig. 10 and Fig. 11 further investigate the effect of various number of channel paths and different FDO factors M. It is clear that, when the oversampling factors M is determined, a better BER performance is obtained as the number of channel paths increases. Meanwhile, when the number of channel paths is determined, BER performance improves as the oversampling factor increases, but only within a limited range, i.e., $M \leq 69/64$. Actually, BER performance highly depends on the number of channels paths, i.e., multipath diversity, which can be fully exacted by choosing $M \leq (N+L-1)/N$. Since the oversampling process increases computational complexity, the FDO-MMSE receiver only chooses $M = (N+L-1)/N$ when the number of channel path L is known to the receiver.

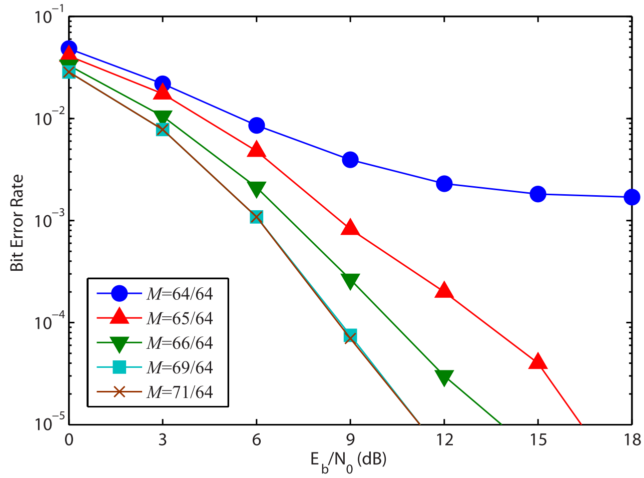

FIGURE 11. Performance comparison of FDO-MMSE receiver using different oversampling factors.

V. CONCLUSION

In this paper, we have proposed a framework of cognitive-CDMA systems by combining the concept of cognitive radio and code division multiple access. With frequency domain oversampling (FDO), the receiver signal is projected to a higher dimension to extract channel diversity inherent to multipath fading channels. As a result, the proposed FDO-MMSE receiver design extends cognitive-CDMA's applications to more severe multipath fading channels, carrier frequency offset and spectrum sensing mismatch. By doing so, cognitive-CDMA systems are of great potential as a transmission technology for internet of things applications.

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