Cluster-based Transform Domain Communication Systems for High Spectrum Efficiency

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Abstract

This paper presents a cluster-based transform domain communication system (TDCS) to improve spectrum efficiency. Unlike the utilities of clusters in orthogonal frequency division multiplex (OFDM) systems, the cluster-based TDCS framework divides entire unoccupied spectrum bins into L clusters, where each one represents a data steam independently, to achieve L times of spectrum efficiency compared to that of the traditional one. Among various schemes of spectrum bin spacing and allocation, the TDCS with random allocation scheme appears to be an ideal candidate to significantly improve spectrum efficiency without seriously degrading power efficiency. In multipath fading channel, the coded TDCS with random allocation scheme achieves robust BER performance due to a large degree of frequency diversity. Furthermore, our study shows that the smaller spectrum bin spacing should be configured for the cluster-based TDCS to achieve higher spectrum efficiency and more robust BER performance.

Index Terms

Spectrum and power efficiency, transform domain communication system (TDCS), cognitive radio

I. INTRODUCTION

Due to the scarcity of available spectrum, future wireless communication systems have to efficiently use all available spectrum resources. The concept of transform domain communication system (TDCS) has been initially studied in [1], where it smartly synthesizes an adaptive waveform by avoiding using spectrum bands occupied by jammers or licensed users. Unlike orthogonal frequency division multiplexing (OFDM) and multi-carrier code division multiple access (MC-CDMA), TDCS is designed to avoid the use of occupied bands by signal processing facilities at both transmitter and receiver instead of mitigating the interference only at receiver [2]. Thus, TDCS can be used as a cognitive radio (CR) modulation technique for overlay opportunistic spectrum access systems [3] [4].

The multiple access TDCS (MA-TDCS) has been first implemented by assigning each user a unique primitive polynomial for a different *m*-sequence [5], and the techniques needed for acquisition and synchronization have also been discussed in [6]. The authors in [7] have proposed an efficient implementation of TDCS to enhance bit error rate (BER) performance by removing the imaginary part of noise components. For practical applications, the problem of peak-toaverage power ratio (PAPR) has been studied to minimize the nonlinear distortion of high power amplifier (HPA) [8]. However, TDCS has been used only for the low-rate control channel in cognitive radio networks because of its low spectrum efficiency [9]. In order to improve spectrum efficiency, a modified TDCS model has been proposed with another data source in the form of embedded symbols [10]. Since it uses the high-order phase shift keying (PSK) modulation, the embedded TDCS achieves unsatisfactory spectrum and power efficiency due to the degraded BER performance with reduced Euclidean distance.

In OFDM systems, the concept of clustering has been widely used for channel estimation [11] or interference suppression [12]. However, the purpose of using clusters is not to improve spectrum efficiency since OFDM is essentially a digital modulation technique where the data stream modulates spectrum bins directly. In this paper, we present a cluster-based TDCS framework to improve spectrum efficiency, based on the fact that it still achieves sufficient orthogonality among different spectrum bins when the number of unoccupied spectrum bins is smaller than the order of cyclic code shift keying (CCSK) modulation [13]. For the *L*-cluster TDCS, the unoccupied spectrum bins are divided into L clusters. We will show that our proposed TDCS achieves L times of spectrum efficiency compared to that of the traditional one.

Similar to many communication scenarios, the cluster-based TDCS encounters the tradeoff between spectrum and power efficiency, i.e., it achieves high spectrum efficiency with a penalty of BER performance as the number of clusters increases [9]. To solve this problem, in this paper, two

spectrum bin allocation schemes are considered, namely the continuous and random allocation schemes. Analytical and simulation results illustrate that, the *L*-cluster TDCS with random allocation scheme achieves L times of spectrum efficiency without serious BER performance degradation, compared to the traditional one. We also find that, different from the result in [13], the spectrum bin spacing of the cluster-based TDCS should be configured as small as possible to achieve high spectrum efficiency and robust BER performance.

We use $(\cdot)^*$ and $|\cdot|$ to represent the operations of conjugate and absolute value. The modulo operation mod(x, y) denotes the remainder of x divided by y. The symbols \mathcal{F} and \mathcal{F}^{-1} represent the operations of fast Fourier transform (FFT) and its inverse (IFFT), respectively. Finally, the symbol \emptyset denotes an empty set.

II. REVIEW ON TRADITIONAL TDCSs

In TDCS, the entire spectrum band is divided into N spectrum bins. A spectrum availability vector, $\mathbf{A} = \{A_0, A_1, ..., A_{N-1}\}$, is used to represent the distribution of spectrum holes as shown in Fig.1. Note that the value of A_k is set to 1 (or 0) if the k_{th} bin is unoccupied (or occupied). Let us assume that there are N_C unoccupied bins inside the set Ω^C , i.e., $\{A_k = 1, k \in \Omega^C\}$ [2]. According to Fig.2, a user-specific complex pseudorandom (PR) phase vector, $\mathbf{P} = \{e^{jm_0}, e^{jm_1}, ..., e^{jm_{N-1}}\}$, is multiplied element by element with \mathbf{A} to produce a spectral vector \mathbf{B} , i.e., $\mathbf{B} = \mathbf{A} \cdot \mathbf{P}$. The fundamental modulation waveform (FMW) b is achieved by performing an IFFT operation,

$$\mathbf{b} = \{b_0, b_1, ..., b_{N-1}\} = \lambda \mathcal{F}^{-1}\{\mathbf{B}\},\tag{1}$$

where $\lambda = \sqrt{N/N_C}$ is an energy normalization factor. With a *M*-ary CCSK modulator, the transmitted waveform, $\mathbf{x} = \{x_0, x_1, \dots, x_{N-1}\}$, is achieved by cyclically shifting b with *S* places [9],

$$x_n = b_{mod\left(n - \frac{SN}{M}, N\right)} = \lambda \sum_{k=0}^{N-1} A_k e^{jm_k} e^{\frac{-j2\pi Sk}{M}} e^{\frac{j2\pi kn}{N}}.$$
 (2)

For detection, the received waveform, $\mathbf{r} = \{r_0, r_1, \cdots, r_{N-1}\}$, is correlated with the local reference FMW to recover input data symbols by detecting the maximum correlation output [14]. To halve noise effects, the receiver extracts only the real part of maximum correlation output,

$$\tilde{S} = \arg \max \left\{ \Re \left\{ \mathcal{F}^{-1} \left\{ \mathcal{F}(\mathbf{r}) \cdot (\mathcal{F}(\mathbf{b}))^* \right\} \right\} \right\},\tag{3}$$

where $\Re \{\cdot\}$ denotes the operator obtaining the real part of a complex quantity.

Since each transmitted waveform carries $\log_2 M$ bits, the spectrum efficiency of traditional TDCS with bandwidth W and spectrum bin spacing Δ_f , i.e., $\Delta_f = W/N$, is given by [13]

$$\eta_{TDCS} = \frac{\Delta_f \log_2(M)}{\gamma W} \text{(bits/s/Hz)}, \tag{4}$$

where γ denotes the unoccupied bandwidth ratio. According to (4), the traditional TDCS should choose M and Δ_f with the highest possible value to improve spectrum efficiency. However, it is emphasized in [13] that Δ_f should be configured as small as possible to achieve noise-like properties for robust BER performance. Obviously, this inherent tradeoff with respect to Δ_f makes it difficult to achieve robust BER performance and high spectrum efficiency simultaneously.

III. CLUSTER-BASED TDCS

From [13], TDCS still achieves sufficient orthogonality among different spectrum bins when the number of unoccupied spectrum bins is smaller than the CCSK modulation order. Therefore, in this paper, a cluster-based TDCS framework is proposed to achieve high spectrum efficiency by dividing the unoccupied spectrum bins into clusters.

We assume that N_C unoccupied spectrum bins are equally divided into L clusters, and each cluster has N_C/L unoccupied spectrum bins. For the l_{th} cluster, the unique spectrum availability vector is defined as $\mathbf{A}^l = \{A_0^l, A_1^l, \dots, A_{N-1}^l\},\$

$$A_k^l = \begin{cases} 1, & k \in \Omega_l^C \\ 0, & k \in \Omega_l \end{cases},$$
(5)

where Ω_l^C and Ω_l denote the sets of unoccupied and occupied spectrum bins for the l_{th} cluster, respectively. To fully utilize all available spectrum resources and maintain orthogonality among different clusters, $\{\Omega_l^C, l = 1, 2, ..., L\}$ should satisfy

$$\bigcup_{l=1,2,\dots,L} \Omega_l^C = \Omega^C \quad \text{and} \quad \bigcap_{l=1,2,\dots,L} \Omega_l^C = \emptyset.$$
(6)

The FMW representing the l_{th} cluster is generated by performing an IFFT operation on the scalar product between \mathbf{A}^l and the PR phase vector \mathbf{P} , i.e. $\mathcal{F}^{-1} \{ \mathbf{A}^l \cdot \mathbf{P} \}$. Then, all FMWs associated with their corresponding clusters are respectively modulated by the CCSK modulation

of an order M. The transmitted waveform $\mathbf{x} = \{x_0, x_1, \dots, x_{N-1}\}$ generated by the *L*-cluster TDCS is given by

$$x_n = \lambda \sum_{l=1}^{L} \sum_{k=0}^{N-1} A_k^l e^{jm_k} e^{\frac{-j2\pi S^l k}{M}} e^{\frac{j2\pi kn}{N}},$$
(7)

where λ is the energy normalization factor given in (1) and $S^l \in \{0, 1, 2, \dots, M-1\}$ denotes the data symbol carried by the l_{th} cluster. It is easy to express (7) into

$$x_n = \lambda \sum_{k=0}^{N-1} \left(\sum_{l=1}^{L} A_k^l e^{jm_k} e^{\frac{-j2\pi S^l k}{M}} \right) e^{\frac{j2\pi kn}{N}}.$$
(8)

Therefore, the transmitter of cluster-based TDCS requires only one IFFT operator, as shown in Fig.3(a).

After passing through an additive white Gaussian noise (AWGN) channel, the received waveform $\mathbf{r} = \{r_0, r_1, \dots, r_{N-1}\}$ is

$$r_n = \lambda \sum_{k=0}^{N-1} \left(\sum_{l=1}^{L} A_k^l e^{jm_k} e^{\frac{-j2\pi S^l k}{M}} \right) e^{\frac{j2\pi kn}{N}} + w_n,$$
(9)

where w_n indicates the AWGN noise. Following the CCSK demodulation shown in Fig.3(b), the data symbol S^l is recovered by detecting the maximum correlation output,

$$\mathbf{y}^{l} = \mathcal{F}^{-1} \left\{ \mathcal{F} \left\{ \mathbf{r} \right\} \cdot \left(\mathbf{A}^{l} \cdot \mathbf{P} \right)^{*} \right\},$$
(10)

where $(\mathbf{A}^{l} \cdot \mathbf{P})$ denotes the frequency-domain local reference FMW associated with the l_{th} cluster. Utilizing the constraint in (6), the τ_{th} element of \mathbf{y}^{l} is derived as

$$y_{\tau}^{l} = \sum_{p=0}^{N-1} \left(\lambda \left| A_{p}^{l} \right|^{2} e^{\frac{-j2\pi S^{l} p}{M}} + \left(\sum_{n=0}^{N-1} w_{n} e^{\frac{-j2\pi pn}{N}} \right) (A_{p}^{l} e^{jm_{p}})^{*} \right) e^{\frac{j2\pi p\tau}{N}}, \tag{11}$$

and the demodulated data symbol \tilde{S}^l is expressed as

$$\tilde{S}^{l} = \arg\max_{\tau} \left\{ \Re \left\{ y_{\tau}^{l} \right\} \right\} = \arg\max_{\tau} \left\{ \Re \left\{ R_{\tau}^{l} + n_{\tau}^{l} \right\} \right\},\tag{12}$$

where

$$R_{\tau}^{l} = \lambda \sum_{p=0}^{N-1} \left(\left| A_{p}^{l} \right|^{2} e^{\frac{-j2\pi S^{l} p}{M}} \right) e^{\frac{j2\pi p\tau}{N}}, \tau = 0, 1, \cdots, N-1$$
(13)

denotes the autocorrelation of the l_{th} FMW, and

$$n_{\tau}^{l} = \sum_{p=0}^{N-1} \left(\sum_{n=0}^{N-1} w_{n} e^{\frac{-j2\pi pn}{N}} (A_{p}^{l})^{*} e^{-jm_{p}} \right) e^{\frac{j2\pi p\tau}{N}}, \tau = 0, 1, \cdots, N-1$$
(14)

denotes the noise obtained by CCSK demodulator. Consequently, the receiver of cluster-based TDCS is shown in Fig.3(b), where data symbols corresponding to other clusters can be recovered by same procedures described above.

Since the cluster-based TDCS can be considered as a group of individual traditional TDCSs where each one carries $\log_2(M)$ bits, the spectrum efficiency of *L*-cluster TDCS is

$$\eta_{Cluster} = \frac{L\Delta_f \log_2(M)}{\gamma W} \text{(bits/s/Hz)}, \tag{15}$$

where W, γ , and Δ_f are defined in (4).

By comparing (4) and (15), the traditional scheme can be considered as a special case (L = 1) of cluster-based TDCS. For a given CCSK modulation order M, the spectrum efficiency is improved only by increasing the spectrum bin spacing Δ_f . However, for the cluster-based TDCS, two variables in (15), L and Δ_f , are associated with the spectrum efficiency $\eta_{Cluster}$. With the concept of clustering, the cluster-based TDCS is consisted of a group of individual traditional ones. This arrangement achieves the spectrum efficiency of L-cluster TDCS to be L times of that achieved by the traditional one.

IV. SPECTRUM BIN ALLOCATION SCHEMES

Similar to many communication scenarios, the cluster-based TDCS has a tradeoff between spectrum and power efficiency. Since the autocorrelation of an ideal FMW has a distinct peak and low sidelobes, CCSK modulation is a form of M-ary signaling over a communication channel [14]. The lower sidelobes the autocorrelation has, the better BER performance TDCS can achieve. However, as the number of clusters L increases, the number of unoccupied spectrum bins in each cluster, i.e. N_C/L , decreases, leading to high autocorrelation sidelobes. In this case, BER performance is highly dependent on sidelobes, especially the first few sidelobes.

To better understand the effect of clustering, let us reinvestigate the autocorrelation in (13). Without loss of generality, we may assume the data symbol $S^l = 0$ for the l_{th} cluster. According to (5), (13) can be rewritten as

$$R_{\tau}^{l} = \lambda \sum_{p \in \Omega_{l}^{C}} e^{\frac{j2\pi p\tau}{N}}, \tau = 0, 1, \cdots, N - 1.$$
(16)

As a consequence of Cauchy-Schwarz inequality [15], for any delay $\tau \neq 0$, $R_0^l \geq R_{\tau}^l$ means that R_0^l is the autocorrelation mainlobe. Thus, the normalized sidelobes are expressed as

$$R_{\tau,norm}^{l} = \frac{R_{\tau}^{l}}{R_{0}^{l}} = \frac{L}{N_{C}} \left(\sum_{p \in \Omega_{l}^{C}} e^{\frac{j2\pi p\tau}{N}} \right), \tau = 1, \cdots, N-1.$$
(17)

From (17), the normalized sidelobes are decided by two factors, the number of clusters L and the set of unoccupied spectrum bins Ω_l^C . The larger L results in higher normalized sidelobes, leading to degraded BER performance. For the set Ω_l^C , two spectrum bin allocation schemes are considered for the cluster-based TDCS, namely continuous and random allocation schemes shown in Fig.4.

The objective of all allocation schemes is to minimize sidelobes $\{R_{\tau,norm}^l, \tau \neq 0\}$ for all *L* clusters. In this paper, minimizing the largest sidelobe is considered under the constraint in (6), and the objective function becomes

$$\beta_{min} = \min \left\{ \max_{l,\tau} \left\{ R_{\tau,norm}^{l}, \tau \neq 0 \right\} \right\}$$

subject to
$$\bigcup_{l=1,2,\dots,L} \Omega_{l}^{C} = \Omega^{C}$$
$$\bigcap_{l=1,2,\dots,L} \Omega_{l}^{C} = \emptyset.$$
(18)

Utilizing the Stirling approximation [16], the global search to find out the minimal β_{\min} requires a complexity of

$$\prod_{l=0}^{L-1} \left(\begin{array}{c} \frac{N_C(L-l)}{L} \\ \frac{N_C}{L} \end{array} \right) = \frac{N_C!}{\left(\frac{N_C}{L}!\right)^L} \sim \left(2\pi N_C\right)^{\frac{1-L}{2}} \cdot L^{N_C + \frac{L}{2}},\tag{19}$$

which means that optimizing the objective function in (18) is a NP-hard problem. As shown in Fig.5, the value of β_{min} can also be approximately found by a finite number of Monte Carlo trials without exhaustive search.

It is obvious that the cluster-based TDCS with the random allocation scheme has a small β_{\min} value, and β_{\min} gradually increases as the number of clusters *L* increases. In fact, with the continuous allocation scheme described in Fig.4(a), the FMW corresponding to each cluster has a small total bandwidth, leading to the associated autocorrelation having high sidelobes. With the random allocation scheme, however, the allocated unoccupied spectrum bins of each cluster are distributed over almost the entire bandwidth. The corresponding FMW hence becomes a wideband signal, leading to low autocorrelation sidelobes. As the CCSK demodulation in (12) relies

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on the FMW with impulse-like autocorrelation properties, the cluster-based TDCS with random allocation scheme is expected to achieve better BER performance than that with continuous allocation scheme.

V. NUMERICAL RESULTS

To validate the cluster-based TDCS, a scenario of spectrum bandwidth W = 10MHz and $\gamma = 3/4$ is considered where the occupied bands are present in the range 2.5~3.75 MHz and 6.25~7.5 MHz. In the simulation, we assume N equals 256 and 1024, and the CCSK modulation order equals N.

A. Performance in AWGN channel

With the continuous and random allocation schemes, Fig.6 shows the BER performance of cluster-based TDCS with N = 256. For a small number of clusters (L = 2), the TDCS with both allocation schemes achieves BER performance similar to the traditional one, indicating that the BER performance is not obviously degraded by doubling spectrum efficiency. Although spectrum efficiency is further improved as L increases, however, the proposed TDCS suffers from BER performance degradation. In particular, the 8-cluster TDCS with random allocation scheme achieves an 8-fold improvement in spectrum efficiency at the cost of 1dB BER degradation, compared to the traditional scheme.

To demonstrate the impact of the number of clusters, L, on the system performance, Fig.7 shows spectrum and power efficiency for N = 256 and 1024 in AWGN channel, i.e., E_b/N_0 (dB) required for BER=10⁻⁴ with L = 1, 2, 4, 8, 16, 32, 64. In accordance with analytical results in section IV, the TDCS with random allocation scheme outperforms that with the continuous scheme in terms of BER performance. For N = 256, the 8-cluster TDCS with random allocation scheme achieves a 9dB gain in terms of E_b/N_0 compared to that with continuous allocation scheme, because of the lower autocorrelation sidelobes.

Similar to the results shown in Fig.6, the cluster-based TDCS suffers from BER degradation when L is large. Taking an example for N = 1024, the 8-cluster TDCS with random allocation scheme requires $E_b/N_0 = 4.1$ dB to achieve BER= 10^{-4} , whereas the 64-cluster TDCS requires $E_b/N_0 = 6.1$ dB. This observation indicates that spectrum efficiency is increased from 0.104 to 0.833 (bits/s/Hz) with a penalty of 2dB in terms of E_b/N_0 to achieve BER= 10^{-4} . Therefore, for practical scenarios, TDCS should choose a suitable value of L to achieve a desirable tradeoff between the spectrum and power efficiency requirement.

B. Performance in multipath fading channel

Let us discuss the performance of coded TDCS in multipath fading channel (COST207RAx6 channel in [17]). A convolution channel code with a coding rate 1/2 is considered. To combat the effects from the multipath fading channel, the length 1/4 cyclic prefix and a minimal mean square error (MMSE) equalizer are simulated.

Fig.8 shows that the TDCS with both allocation schemes achieves degraded BER performance when L increases. It is also interesting to observe that, for L = 2, the TDCS with random allocation scheme is superior to that with the continuous scheme, in contrast to the AWGN channel case where both allocation schemes achieve similar BER performance. Compared to the continuous allocation scheme, each FMW associated with random allocation scheme spreads over a wider spectrum. Therefore, the cluster-based TDCS with random allocation scheme achieves better BER performance than that with continuous scheme, due to a larger degree of frequency diversity in multipath fading channel [18].

Fig.9 illustrates the spectrum and power efficiency in multipath fading channel, where the TDCS with random allocation scheme still achieves better spectrum and power efficiency, compared to that with continuous allocation scheme. Furthermore, the cluster-based TDCS suffers from obvious BER degradation when L exceeds a certain threshold value. According to the simulation results, the number of clusters should be $L \leq 4$ for N = 256 and $L \leq 16$ for N = 1024.

According to the system performances in AWGN and multipath fading channels, we make the following remarks.

• To achieve better spectrum and power efficiency, the cluster-based TDCS should adopt the random allocation scheme. Since the randomly allocated bins are distributed over almost the entire bandwidth, the generated FMW has low autocorrelation sidelobes leading to the robust BER performance. Furthermore, in multipath fading channel, the proposed TDCS with random allocation scheme achieves more robust BER performance due to a larger degree of frequency diversity, compared to that with continuous allocation scheme.

- Due to the tradeoff between spectrum and power efficiency, the cluster-based TDCS cannot unlimitedly increase spectrum efficiency. When L exceeds the specific threshold value, such as L = 4 for N = 256 and L = 16 for N = 1024, BER performance rapidly degrades. This observation provides a quick rule of thumb for designing the cluster-based TDCS.
- The traditional scheme can be considered as a special case (L = 1) of cluster-based TDCS, where only a large value of spectrum bin spacing Δ_f can improve spectrum efficiency. Under the constraint of a small value Δ_f for robust BER performance, this inherent tradeoff makes it difficult to achieve robust BER performance and high spectrum efficiency simultaneously. Fortunately, with the concept of randomly clustering, the cluster-based TDCS with a smaller Δ_f achieves higher spectrum efficiency and more robust BER performance.

VI. CONCLUSION

In this paper, we have proposed a cluster-based TDCS framework to improve spectrum efficiency by dividing all unoccupied spectrum bins into clusters. Among various schemes of spectrum bin spacing and allocation, analytical and simulation results show the proposed TDCS with random allocation scheme achieves higher spectrum efficiency and more robustness against BER performance degradation, compared to that with continuous allocation scheme. Furthermore, different from previously reported conclusions in the literature, the cluster-based TDCS should configure a smaller spectrum bin spacing Δ_f to achieve higher spectrum efficiency and more robust BER performance.

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



Fig. 2. Block diagram of the traditional TDCS



(b) Reciever of cluster-based TDCS

Fig. 3. Block diagram of the cluster-based TDCS



Fig. 4. Spectrum bin allocation schemes. (Spectrum bins marked with the same symbol denote the same cluster)



Fig. 5. Minimal value of the largest sidelobes obtained from 10^4 Monte-Carlo trials



Fig. 6. BER performance of the cluster-based TDCS in AWGN channel (N = 256, and L = 2, 8, 32, dashed line: continuous, solid line: random)



Fig. 7. Spectrum and power efficiency of the cluster-based TDCS in AWGN channel (L = 1, 2, 4, 8, 16, 32, 64 and BER= 10^{-4} , dashed line: continuous, solid line: random)



Fig. 8. BER performance of the coded cluster-based TDCS in multipath fading channel (N = 256, L = 2, 4, 8, dashed line: continuous, solid line: random)



Fig. 9. Spectrum and power efficiency of the coded cluster-based TDCS in multipath fading channel (L = 1, 2, 4, 8, 16, 32, 64, BER= 10^{-4} , dashed line: continuous, solid line: random)