Design of a Multi-Carrier Different Chaos Shift Keying Communication System in Doubly Selective Fading Channels

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***Abstract*—In this paper, a novel chaos modulation scheme, which combines code-shifted differential chaos shift keying (CS-DCSK) with orthogonal frequency division multiplexing (OFDM) is presented, namely OFDM-CS-DCSK. In the proposed scheme, the reference signal and the information bearing signal of CS-DCSK are firstly formed by Walsh code sequences, then different chips of the CS-DCSK signal are mapped onto different subcarriers of OFDM. Utilizing the characteristics of OFDM and CS-DCSK, the proposed scheme has robust performance over time-frequency doubly selective fading channel. In addition, the proposed system has low complexity because channel estimation, channel equalizer and the radio frequency (RF) delay circuits are not required at its receiver. By the computer simulations, bit error rate (BER) performances of the proposed scheme are compared with OFDM-DCSK and CS-DCSK under various channel parameters. Simulation results indicate that the proposed scheme has significant performance advantages over OFDM-DCSK and CS-DCSK in time-frequency doubly selective fading channel.**

***Index Terms*—Orthogonal frequency division multiplexing(OFDM), Code-Shifted Differential Chaos Shift Keying(CS-DCSK), time-frequency doubly selective fading channel**

I. Introduction

With the widespread use of mobile devices, it is expected that wireless equipment will reach 700 million units by 2020 [1]. Complex transmission environments, interference and information security are and will continue to be a huge challenge for reliable transmission, especially for selective fading channels.

Time-frequency doubly selective fading channels are typically harsh environments for wireless communications. For example, in underwater acoustic wireless networks, due to multipath propagation, Doppler spread and Doppler shift, the transmitted signal is greatly destroyed [2], [3]. In order to implement reliable communication over doubly selective fading channel, a large number of techniques have been proposed. One technique is using multi-carrier systems, such as orthogonal frequency division multiplexing(OFDM). OFDM has a good advantage of mitigating frequency selective fading of channel, because when the bandwidth of each subcarrier is smaller than the coherence bandwidth, each subcarrier can be assumed to pass a flat fading channel [4]. However, OFDM systems may experience significant intercarrier interference(ICI) when the channel is a time-frequency doubly selective fading channel [5]. There are some schemes proposed to mitigate the ICI in time varying channel [6], [7]. The technique of using antenna diversity at the receiver is proposed in [6]. However, with the increasing of normalized Doppler spread, the effect of antenna diversity is decreased [8]. The linear minimum mean-squared error (MMSE) symbol estimation is an effective scheme [7], but traditional MMSE estimators normally have a high computational complexity, which needs a large matrix inversion [9]. Several algorithms to reduce the computational complexity are also developed in [10]–[12]. In [12], a low-complexity iterative symbol estimation scheme is presented, which leverages the ICI-shortened channel representation.

Another effective technique to solve this problem is spread-spectrum(SS) methods, such as chaotic spreading sequences. Chaotic signals provide a low cost and confidentiality way for communications, which have random-like sharp autocorrelation, low cross-correlation and low probability of interception(LPI) characteristics [13]. The chaos-based modulation can offer excellent system performance as an optional spread-spectrum communication, where communication channel suffers from multipath propagation and distortion [14]. Furthermore, differential chaos shift keying(DCSK) can be implemented without complex channel estimation and synchronization [15]. However, in the DCSK system, reference signal and information bearing signal are transmitted in two equal succession slots which require an RF delay at DCSK reveiver [16]. In [17], Xu et al. presented a code shifted differential chaos shift keying (CS-DCSK). In this system, reference signal and information signal are overlapping in time domain, but they are orthogonal in code domain using Walsh code sequences. This system not only overcomes the problem of RF delay line at the receiver, but also has a good performance in time-varying channel. However, in frequency selective fading channel, if the maximum multipath delay (τ_m) of channel is large (it is not agree with condition $\tau_m \ll \beta$), the BER performance will show error floor.

Moreover, several techniques of combining multi-carrier and spread spectrum are proposed, such as OFDM-DCSK [18], multi-carrier code-division multiple-access (MC-CDMA) [19], multi-carrier direct-sequence CDMA (MC-DS-CDMA) [20]. In OFDM-DCSK, the reference signal is firstly transmitted in all subcarriers by one pilot OFDM symbol and the information bearing signals are transmitted in the next following

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OFDM symbols [18]. In MC-CDMA, one transmitted symbol is spread over a number of orthogonal subcarriers in the frequency domain [19]. In MC-DS-CDMA, the symbol is first spread in time domain, then spread in frequency domain [20]. For the above systems, they are robust in frequency selective channel while having defects in time selective channel caused by Doppler spread. Thus, in order to mitigate this destructive effect, Doppler diversity has been proposed in [21], [22]. For example, in [22], the MC-CDMA systems improves the performance by exploiting Doppler diversity in fast fading channel. However, these schemes use coherent receiver with channel estimator and equalizer, which increase the complexity of the receiver.

In this paper, a new design of a multi-carrier DCSK system is proposed. The system is a hybrid of OFDM and CS-DCSK. On the transmitter, the reference signal and information bearing signal are overlapping in time domain, and they are orthogonal in code domain by Walsh code sequences. Then, the different chips of CS-DCSK signal are modulated on a group of orthogonal subcarriers. In this case, the proposed system is robust against time-frequency doubly selective fading due to the characteristics of CS-DCSK and OFDM. Furthermore, this system is easy to implement since the channel estimator and equalizer at receiver are not required. By comparing the BER performance of the proposed system with OFDM-DCSK and CS-DCSK in time-frequency doubly selective fading channel, the merits of the proposed system are validated. The remainder of this paper is organized as follows. In Section II, system model of the OFDM-CS-DCSK is described. Numerical results are presented in Section III. Concluding remarks are presented in Section IV.

II. System Model

The proposed OFDM-CS-DCSK system is depicted in Fig. 1. In this system, a frame of transmitted signal comprises a reference signal and M information bearing signals, where the reference signal and M information bearing signals are superimposed in the time domain and they are orthogonal to each other in code domain by using Walsh code sequences. Reference signal is the corresponding product of N same fragments and N-length Walsh code $\mathbf{w}_R = [w_{R,1}, w_{R,2}, \cdots, w_{R,N}]$ where one fragment comprises β chaos chips. Chaos chips are produced by a logistic map function $c_{i+1} = 1 - 2{c_i}^2, i \in N^+$ with a chip period T_c. There are M information symbols, $\mathbf{a} = \{a_1, a_2, \cdots, a_M\}$, modulated on M information bearing signal in one frame of transmitted signal. The i-th $(1 \leq \mathrm{i} \leq M)$ information bearing signal is replicas of the chaos chips of reference signal which is modulated by information symbols a_i and Walsh code $\mathbf{w}_{I_i} = [w_{I_i,1}, w_{I_i,2}, \cdots, w_{I_i,N}]$. In a word, the duration of a multiple carrier symbol is $N\beta T_c$.

As shown in Fig. 1, a frame of transmitted signal contains $N\beta$ chips with period T_c. By using orthogonal frequency division multiplexing, $N\beta$ chips are loaded onto $N\beta$ mutually orthogonal subcarriers. Finally, cyclic prefix is inserted. Therefore, a baseband equivalent signal can be expressed as

$$s(t) = \sum_{m=1}^{N\beta} \left[d(m) \mathrm{rect}(t) e^{j2\pi m \Delta f t} \right] \tag{1}$$

where $d(m)$ is CS-DCSK signal with,

$$d(m) = \mathbf{w}_R \otimes \mathbf{c} + \sum_{i=1}^{M} a_i \left(\mathbf{w}_{I_i} \otimes \mathbf{c} \right), \quad m = 1, \cdots, \beta N \tag{2}$$

where $\mathbf{c} = \{c_1, c_2, \cdots, c_\beta\}$ is a β-length chaos sequence with zero mean, unity mean squared value, i. e., $\mathrm{E}(c_i) = 0$ and $\mathrm{E}(\mathrm{c_i^2}) = 1$, $a_i \in \{-1, +1\}$ is the i-th modulated information symbol. $\mathbf{w}_\mathrm{R} = [w_{R,1}, w_{R,2}, \cdots, w_{R,N}]$ and $\mathbf{w}_{I_i} = [w_{I_i,1}, w_{I_i,2}, \cdots, w_{I_i,N}]$ denote mutually orthogonal Walsh code sequences, N is the length of Walsh code sequence, $\otimes$ is Kronecker product. $T_s = \beta T_c$ is the length of fragment, $N\beta$ is the number of the subcarriers, $m\Delta f$ is the frequency of m-th subcarrier, $\Delta f = \frac{B}{N\beta}$ is bandwidth of subcarriers, B is bandwidth of system. $\mathrm{rect}(t)$ is a rectangle function,

$$\mathrm{rect}(t) = \begin{cases} 1, & t \in [0, N\beta T_c] \\ 0, & \mathrm{otherwise} \end{cases} \tag{3}$$

At the receiver side, the received signal $r(t)$ is firstly sampled with T_c as a sampling interval, thus, the discrete signal is obtained. The n-th $(1 \leq n \leq N\beta)$ sample of the received discrete symbols can be represented by

$$r_n = \sum_{i=1}^{L} h_i^{(n)} s((n-i))_{N\beta} + \eta_n \tag{4}$$

where $h_i^{(n)}$ is the i-th channel tap at time instant $t = n * T_c$ of time-frequency doubly selective fading channel, L is the number of paths of doubly selective fading channel, $((\bullet))_{N\beta}$ denotes a cyclic shift in the base of $N\beta$, η_n is the additive Gaussian noise with zero mean and variance $N_0/2$.

The receiver structure of proposed system is illustrated in Fig. 2. At first, cyclic prefix is removed and the $N\beta$ received discrete samples are converted from serial signal to parallel. Then, a size of $N\beta$ FFT is used for the received discrete parallel signals to demodulate information chips from subcarriers. Thus, the k-th $(1 \leq k \leq N\beta)$ regenerated chip of signal can be expressed as

$$R_k = S_k H_{k,k} + \underbrace{\sum_{i=1, i\neq k}^{N\beta} H_{k,i} S_i}_{ICI} + N_k \tag{5}$$

where N_k is the noise of k-th subcarrier in frequency domain and $H_{k,d}$ is defined as

$$H_{k,d} = \frac{1}{N\beta} \sum_{i=1}^{L} \sum_{n=1}^{N\beta} h_i^{(n)} e^{\frac{-j2\pi(nd + i(k-d))}{N\beta}} \quad 1 \leq k, d \leq N\beta \tag{6}$$

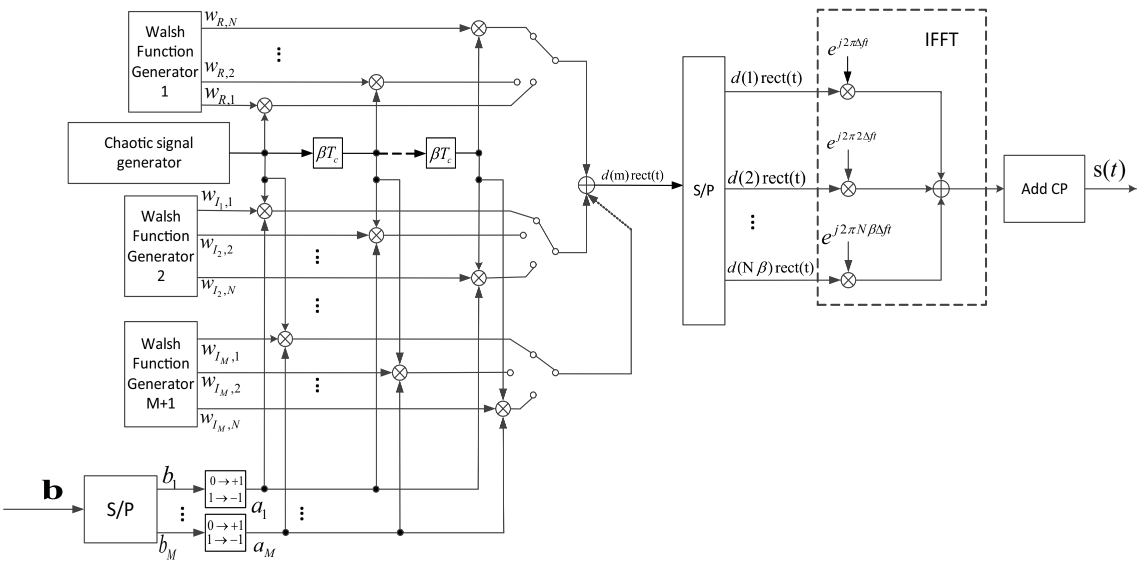

Fig. 1. Transmitter structure of OFDM-CS-DCSK system.

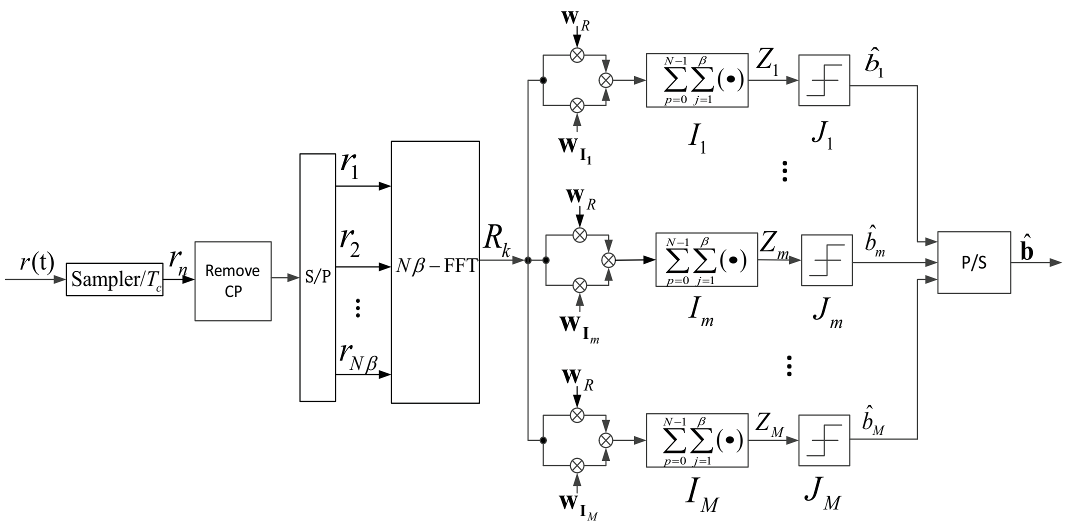

Fig. 2. Receiver structure of OFDM-CS-DCSK system.

Then, the signal is copied onto the M branches in Fig. 2 after FFT transformation. According to the received structure, the output of the m-th branch is

$$Z_m = \mathrm{Re}\left[\sum_{p=0}^{N-1}\left(w_{R,p+1}w_{I_m,p+1}\sum_{j=1}^{\beta}R_{p\beta+j}R_{p\beta+j}^{*}\right)\right] \quad (7)$$

where $\mathrm{Re}(x)$ denotes real part of variable x. So, we can get estimated symbol a_m by

$$\hat{a}_m = \mathrm{sign}(Z_m) \quad (8)$$

Note that, in (5), we can see that the ICI arises due to significant time-varying channel impulse response during of symbol. However, in the proposed system, we do not use ICI equalization at receiver, and only apply the non-coherent receiver which is the same with the CS-DCSK system. From the simulation in Section III, the proposed multicarrier scheme can mitigate the effect of ICI, and show an excellent performance in doubly selective channel.

III. NUMERICAL RESULTS AND DISCUSSIONS

In this section, the BER performance of OFDM-CS-DCSK system over the time-frequency doubly selective fading channel are evaluated by computer simulations. In all simulations, f_{norm} means normalized Doppler spread which is defined by $f_{norm} = f_d T_c$, here f_d is Doppler spread and T_c is chip duration, L is the number of paths of doubly selective fading channel, CP is the length of cyclic prefix. For doubly selective fading channel, we consider a dense resolvable multipath

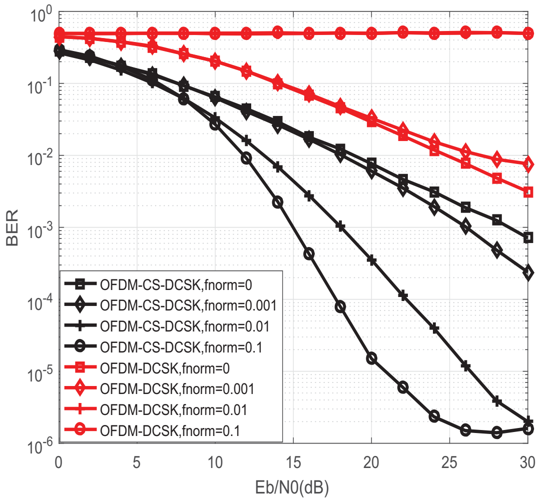

Fig. 3. Comparisons of BER performance between OFDM-CS-DCSK and OFDM-DCSK over frequency flat fading channel with different normal Doppler spread. The parameters are $f_{norm} = 0, 0.001, 0.01, 0.1$; $L = 1$; $CP = 8$.

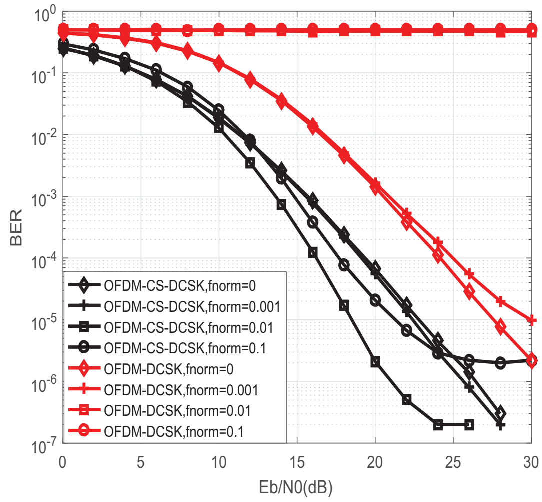

Fig. 5. Comparisons of BER performance between OFDM-CS-DCSK and OFDM-DCSK over doubly selective fading channel. The parameters are $f_{norm} = 0, 0.001, 0.01, 0.1$; $L = 3$; $CP = 8$.

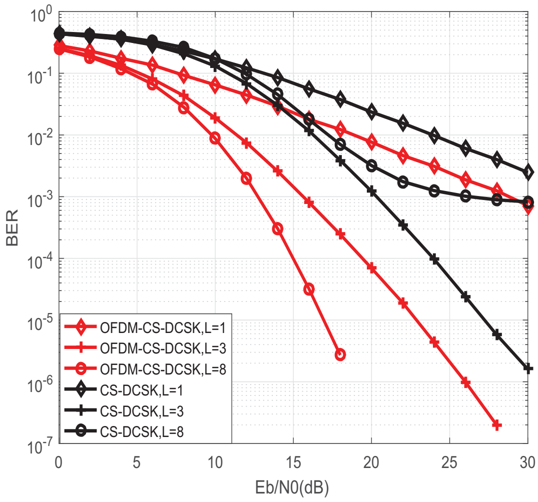

Fig. 4. Comparisons of BER performance between OFDM-CS-DCSK and CS-DCSK over frequency selective fading channel. The parameters are $f_{norm} = 0$;$L = 1, 3, 8$; $CP = 8$.

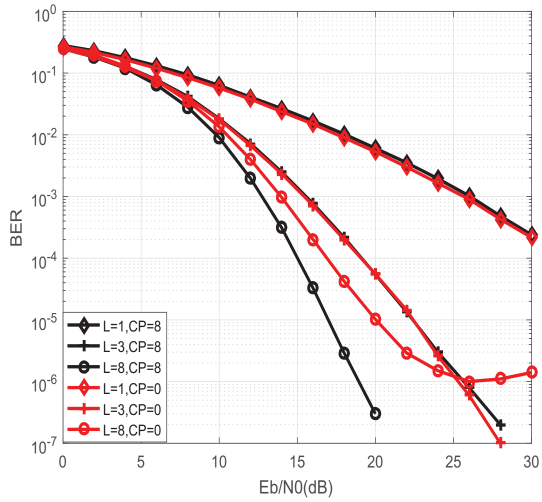

Fig. 6. BER performance of the OFDM-CS-DCSK system over doubly selective fading channel. The parameters are $f_{norm} = 0.001$; $L = 1, 3, 8$; $CP = 0, 8$.

channel, where each multipath gain is Rayleigh distributed with average power $\mathrm{E}\{(h_l^{(n)})^2\}$, where $\mathrm{E}\{(h_l^{(n)})^2\} = \mathrm{E}\{(h_l^{(n)})^2\}\exp\left[-\varepsilon(l-1)\right]$, for $l = 1, 2, ..., L$, are normalized such that $\sum_{l=1}^{L} \mathrm{E}\{(h_l^{(n)})^2\} = 1$. Unless otherwise stated, spreading factor and the number of subcarriers are both 64, the channel parameter ε is set to 1, i. e., uniform power dispersion profile (PDP) channel, the number of information bearing M is 1 in all the following simulations.

Figure 3 shows the performance of OFDM-CS-DCSK and OFDM-DCSK over frequency flat fading channel $(L = 1)$ with $f_{norm} = 0, 0.001, 0.01, 0.1$. From this figure, we can see that OFDM-CS-DCSK has better performance than that of OFDM-DCSK in this channel. For fixed $L = 1$, the performance of OFDM-CS-DCSK improves with the increasing of f_{norm}. From this figure, we also see that the slope of BER curves increase with the increasing of normalized Doppler spread, i. e., the larger f_{norm} is the larger slope is. Although the BER shows error floor when f_{norm} is 0.1 at high signal to noise ratio (SNR) range, BER can still reach 10^{-6}. The phenomenon indicates that the proposed system can obtain Doppler diversity over fast time varying fading channels. In contrast, for OFDM-DCSK system, the BER performance is deteriorated when f_{norm} increases. Especially, there is an obvious error floor at BER level above 10^{-1} when the normalized Doppler spread is larger than 0.01 for all SNR range. Thus, the OFDM-DCSK is not available for fast time-varying fading channel.

Figure 4 shows the performance of OFDM-CS-DCSK and CS-DCSK over static frequency selective fading channel with different number of paths. From the figure, we can see that the slope of the BER curves are same for both systems when the number of path is 1 or 3, i. e., both systems achieve same diversity gain. However, the BER performance of CS-DCSK shows an obvious error floor at BER level 10^{-3} for $L = 8$ since the inter frame interference (IFI) of CS-DCSK can not be neglected when L is large. The results indicate that both systems obtain same frequency diversity order for small maximum multipath delay. But for large maximum multipath delay (large L), the OFDM-CS-DCSK shows a stronger robustness than CS-DCSK.

Figure 5 shows the BER performance of OFDM-CS-DCSK and OFDM-DCSK over doubly selective fading channel with $L = 3$ and $f_{norm} = 0, 0.001, 0.001, 0.01, 0.1$. From this figure, one can see that the slope of the BER curves of both systems are almost same when the normalized Doppler spread is very small. In other word, both systems can achieve the same frequency diversity gain over quasi static frequency selective fading channel. However, the performance of OFDM-DCSK deteriorates with the increasing of f_{norm}. Moreover, when f_{norm} is large, such as $f_{norm} = 0.01$, the BER level is only reduced to 10^{-1} even when $SNR = 30$dB. As for OFDM-CS-DCSK system, when f_{norm} is smaller than 0.1, the BER performance improves with the increasing of f_{norm} above BER level 10^{-7}. For $f_{norm} = 0.1$, the BER decreases to 10^{-5} as SNR increases, although an error floor arises when SNR goes beyond $20dB$. Thus, we can find that the OFDM-CS-DCSK system has good robustness in time-frequency doubly selective fading channel.

Finally, we investigate the effect of cyclic prefix CP on the BER performance of OFDM-CS-DCSK over doubly selective fading channel. To that end, we set normalized Doppler spread $f_{norm} = 0.001$ and the number of fading path $L = 1, 3, 8$, respectively. Figure 6 plots the BER performance of OFDM-CS-DCSK with $CP = 8$ and $CP = 0$. From the figure, we can see that when L is small, cyclic prefix does not have much effect on transmission performance. When L becomes larger, for example $L = 8$, the BER performance of system without cyclic prefix is worse than that of the system with cyclic prefix, because the inter symbol interference (ISI) is aggravated with increasing of L. However, despite the decrease in BER performance, the performance is still good. The above results show that the proposed system can achieve a good performance without cyclic prefix even if in the severe frequency selective fading channel. Therefore, we can sacrifice some performance to increase throughput of the system without cyclic prefix, i. e. , there is a trade-off between transmission performance and spectrum efficiency.

As can be seen from above figures, OFDM-DCSK behaves bad performance in time selective fading channel, but good in frequency selective fading channel. On the other hand, CS-DCSK presents good performance in time selective fading channel, but a bad performance over severe frequency selective fading channel. Thus, by exploring the advantages of OFDM-DCSK system and CS-DCSK system, the proposed OFDM-CS-DCSK system shows excellent performance over doubly selective fading channels.

IV. Conclusion

In this paper, we present a novel non-coherent multi-carrier chaos modulation scheme without channel estimation and equalization at the receiver. This system has excellent performance over time-frequency doubly selective fading channels. The BER performance of the proposed system is compared with CS-DCSK and OFDM-DCSK. Simulations results show that the proposed system has good robustness over doubly selective fading channels, and it has better performance than the other two systems. According to the characteristics of the proposed system, it is a good candidate for high speed mobile wireless networks and underwater acoustic communications.

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