Hindawi Publishing Corporation
Journal of Electrical and Computer Engineering
Volume 2015, Article ID 367693, 10 pages
http://dx.doi.org/10.1155/2015/367693

Research Article

A Scaling Scheme for DCT Precoded Optical Intensity-Modulated Direct Detection Systems

Zhongpeng Wang,[1,2] Xiumin Wang,[3] Fangni Chen,[1] Weiwei Qiu,[1] and Linpeng Ye[1]

[1] *School of Information and Electronic Engineering, Zhejiang University of Science and Technology, Hangzhou 310023, China*
[2] *State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China*
[3] *College of Information Engineering, China Jiliang University, Hangzhou 310018, China*

Correspondence should be addressed to Zhongpeng Wang; wzp1966@sohu.com

Received 9 September 2015; Accepted 12 November 2015

Academic Editor: Iraj Sadegh Amiri

A scaling technique is employed to improve the performance of a Discrete Cosine Transform (DCT) precoded optical intensity-modulated direct detection (IM/DD) OFDM system, which fully exploits the dynamic range of a digital-to-analog converter (DAC). The theoretical analysis shows that the proposed scaling scheme can improve the BER performance of DCT precoded and scaled OFDM systems. The experiment results also show that the proposed scheme significantly improves the BER performance without changing the receiver structure. The measured received sensitivity at a BER of 10^{-3} for a 4 G samples/s (2.7 Gbits/s) DCT precoded and scaled OFDM signal and after 100 km standard single-mode fiber (SMF) transmission has been improved by 3 and 1.3 dB when compared with the original OFDM system and conventional DCT precoded OFDM system, respectively.

1. Introduction

In recent years, optical transmission systems employing orthogonal frequency division multiplexing (OFDM) have gained interest because OFDM can combat fiber chromatic dispersion and polarization mode dispersion. However, the high peak-to-average ratio (PAPR) of OFDM signals is the main problem in the optical OFDM system. A large PAPR will cause strong nonlinear impairment such as self-phase modulation (SPM) and cross-phase modulation (XPM), which are caused by optical signal intensity fluctuation [1]. Therefore, a large number of PAPR reduction schemes have been proposed for applications in optical communication systems, such as clipping [2, 3], Hadamard precoding [4], DFT precoding [5, 6], combined Hadamard and companding transforms [7], Partial Transmit Sequence (PTS) [8], and Selected Mapping (SLM) [9, 10]. There are also other PAPR reduction schemes, such as power-concentrated subcarrier and preemphasis, which have been proposed by other researchers [11, 12]. These PAPR reduction methods can be mainly divided into two domain methods: frequency domain method and time domain method [13]. The frequency domain method is used before the IFFT to decrease the autocorrelation of the input signal of the IFFT and furthermore decrease the peak value of output signal of the IFFT. Precoding, SLM, and PTS schemes are examples of frequency domain methods. Time domain method is used after the IFFT by distorting the signal to reduce the PAPR of the signal. Clipping, companding, and peak widowing belong to the time domain methods. Among all methods, precoding technique is very popular due to its advantages. The attractive features of the precoding method are utilized in OFDM systems to obtain noticeable PAPR reduction with lower complexity and BER performance improvement.

In [14], a spectral shaping for DFTS-OFDM is studied to reduce the PAPR leading to further improvement in nonlinear tolerance. In [15], the theoretical analysis and simulation results show that precoding technique can improve the BER performance of the precoded radio frequency (RF) OFDM system compared with the conventional RF OFDM system.

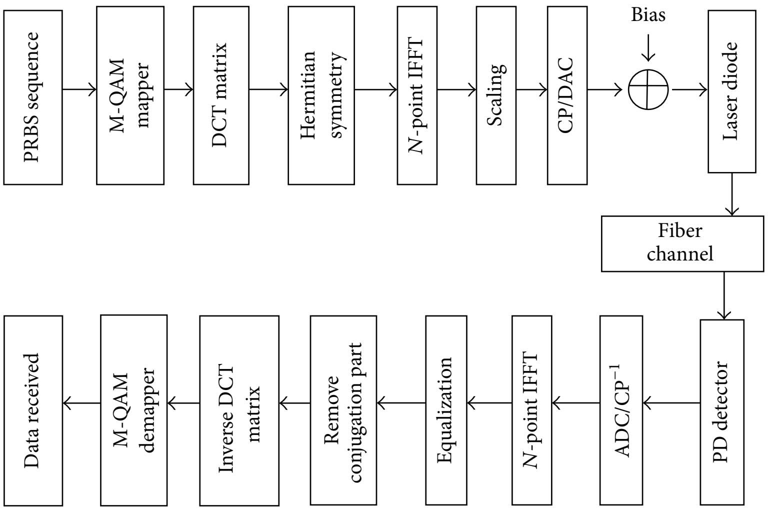


Figure 1: Conceptual diagram for a DCT precoded IM/DD optical OFDM system with scaling.

Reference [16] researched various precoding techniques for PAPR reducing in optical wireless OFDM system by simulation. Reference [17] researched DCT precoding in optical fast OFDM system by simulation. The experimental results show the DCT precoding scheme can improve the BER and PAPR performances of the optical OFDM systems.

In [18], we have recently proposed a combined DCT and clipping scheme to reduce the PAPR for IM/DD optical OFDM system. Furthermore, the experimental results show that the proposed scheme can obtain a considerable BER performance improvement. However, the improvement of BER performance of the proposed scheme is not significant when it is compared with that of the DCT precoded OFDM. On the other hand, clipping algorithm in baseband signal adds the computational complexity of system.

Recently, the authors in [19] proposed an adaptive scaling and biasing scheme to improve BER performance of OFDM-based visible light communication (VLC) systems by simulation. The main idea in [19] is that the output of the IFFT of the VLC system can be amplified using an adaptive scaling in order to improve the BER performance of the system by fully exploiting the dynamic range of the light emitting diodes. Inspired by the concept in [19], we proposed a scaling scheme to improve the BER performance of the conventional DCT precoded IM/DD optical OFDM systems. The PAPR of the DCT precoded OFDM is lower than that of the conventional OFDM. Thus, in order to full exploit the dynamic range of the DAC of a DCT precoded OFDM system, a digital scaling technique can be employed before the digital-to-analog converter (DAC) to improve the SNR of the system. Furthermore the BER performance can be improved without changing the structure of the receiver. Compared to the conventional DCT precoded OFDM, the advantage of the proposed method does not need to add any hardware device. The proposed scaling scheme is employed in an optical direct detection OFDM experimental platform; a sample rate of 4 Gs/s precoded and scaled OFDM signal is successfully processed and recovered after 100 km transmission through SMF link. The experimental results show that the sensitivity of the received DCT precoded and scaled OFDM signal is greatly improved compared to the conventional DCT precoded optical OFDM system and original optical OFDM system.

This paper is organized as follows. In Section 2, the system principle of the proposed scheme is described and the BER performance of the system with scaling is analyzed. In Section 3, the experiment setup of the proposed system is presented. In Section 4, the PAPR and BER performance of the system are evaluated. Finally, Section 5 concludes this paper.

2. System Principle

2.1. System Model. A DCT precoded optical IM/DD OFDM system model using scaling technique is shown in Figure 1. It consists of transmitter, channel, and receiver blocks which are described in Figure 1.

The main idea of the proposed scheme is that the baseband modulated data stream is first transformed by the DCT matrix. Then, the transformed data are processed by the IFFT unit. The proposed scaling is applied before the DAC of the IM/DD optical OFDM system. In order to produce the real output of the IFFT, the input of the IFFT must be a Hermitian symmetric structure.

At the transmitter the binary input data is modulated by a quadrature amplitude modulation (QAM) format. The baseband modulated QAM signal vector is represented by $S = [S_0 \;\; S_1 \;\; \cdots \;\; S_{D-1}]^T$, where $[\cdot]^T$ denotes the matrix transpose. Then the baseband modulated signal vector is passed through S/P converter which generates a complex signal vector of size D. Then DCT precoding is applied to this complex vector which transforms this complex vector into new signal vector of length D. This new signal vector transformed by DCT precoding can be expressed as

$$Y = \mathrm{FS} = [Y_0 \;\; Y_1 \;\; \cdots \;\; Y_{D-1}]^T . \qquad (1)$$

The lth element of Y can be calculated as

$$Y_l = a_l \sum_{d=0}^{D-1} S_d \cos\left[\frac{\pi(2d+1)l}{2D}\right], \quad l = 0, 1, \ldots, D-1, \tag{2}$$

where a_l is defined as

$$a_l = \begin{cases} \sqrt{\dfrac{1}{D}}, & l = 0 \\ \sqrt{\dfrac{2}{D}}, & l \neq 0. \end{cases} \tag{3}$$

DCT precoding matrix F of size D-by-D can be using

$$F_{l,d} = \begin{cases} \dfrac{1}{\sqrt{D}}, & l = 0,\ 0 \le d \le D-1 \\ \sqrt{\dfrac{2}{D}} \cos\left[\dfrac{\pi(2d+1)l}{2D}\right] & 1 \le l \le D-1,\ 0 \le d \le D-1. \end{cases} \tag{4}$$

$F_{l,d}$ means the lth row and dth column of DCT precoding matrix F.

After precoding operation, a signal vector $Z = [Y_0\ Y_1\ \cdots\ Y_{D-1}\ Y_{D-1}^*\ Y_{D-2}^*\ \cdots\ Y_0^*]$ of size $2D$ can be formed. In order to estimate the frequency response of fiber channel in receiver, N_p pilot data symbols $X_p = [X_p(0)\ X_p(1)\ \cdots\ X_p(N_p-1)]$ are uniformly inserted into Z with V subcarriers apart from each other, where $V = 2D/N_p$. After that, the transmitted signal vector X of size N can be written as

$$[0\ X_1\ X_2\ \cdots\ X_{N/2-1}\ 0\ X_{N/2-1}^*\ \cdots\ X_2^*\ X_1^*]. \tag{5}$$

According to the property of IFFT, a real-valued time domain signal x_n corresponds to a frequency domain X_k that is Hermitian symmetric; that is,

$$X_k = X_{N-k}^*, \quad 1 \le k \le N-1, \tag{6}$$

where $*$ denotes complex conjugate. The 0th and $N/2$nd subcarrier are null; that is, $X_0 = 0$, $X_{N/2} = 0$.

After doing IFFT operation to X, the N-point of the IFFT generates the real-valued OFDM signals, and it can be written as

$$x_n = \frac{2}{\sqrt{N}} \sum_{k=1}^{N/2-1} \left(\Re(X_k) \cos\left(\frac{2\pi kn}{N}\right) - \Im(X_k) \sin\left(\frac{2\pi kn}{N}\right) \right), \quad n = 0, 1, \ldots, N-1, \tag{7}$$

where $\Re(\cdot)$ and $\Im(\cdot)$ denote the real part and imaginary part of a complex number X_k, respectively.

The PAPR of the DCT precoded OFDM signal is lower than that of the original OFDM signal without DCT precoding. In order to fully exploit the dynamic range of the DAC we may rescale the DCT precoded OFDM signal so that the maximum amplitude of the DCT precoded OFDM signal is the same as the maximum amplitude of the original OFDM signal. We denote the scaling factor of this linear transformation by β. The scaled signal is then given by βx_n.

After parallel-to-serial, CP addition and DAC, the analog amplified DCT precoded OFDM electronic signal is completed and is then biased and used for modulating the MZM. Assume U_{DC} denote the bias. Then the biased signal takes the form

$$z_n' = (\beta x_n + U_{\mathrm{DC}})^+, \tag{8}$$

where U_{DC} is bias value and $(y)^+ = \max(0, y)$.

At the receiver, the optical signal is detected by a photodiode (PD) detector and converted to the electronic signal. We denote the discrete impulse response of the fiber link by h_n; then the received signal in the discrete form can be expressed as

$$r_n = z_n \otimes h_n + w_n, \tag{9}$$

where w_n is a noise component. The noise component w_n consists of short-noise and thermal-noise, which is introduced at the receiver and may be modeled by an additive white Gaussian noise (AWGN) process with zero mean and variance σ_w^2 [20].

After serial-to-parallel (S/P) conversion and CP removal the received signal $r = [r_1\ r_2\ \cdots\ r_{N-1}]$ is then demodulated to the frequency domain by FFT. The demodulated signal can be expressed as

$$R = HX + W. \tag{10}$$

Let each element of R be expressed as

$$R_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} r_n e^{2\pi kn/N}, \quad k = 0, 1, \ldots, N-1. \tag{11}$$

In the receiver end, the values of the pilot symbols are known and the received pilot symbols R_p are extracted from the received OFDM signal. So the estimated channel information at pilot subcarriers with least square (LS) is calculated by

$$\widehat{H}_p(m) = \frac{R_p(m)}{X_p(m)} \quad m = 0, 1, \ldots, N_p - 1. \tag{12}$$

Then channel information on the data subcarriers can be extracted by employing linear interpolation scheme, where the channel estimation at the data subcarrier between two pilot subcarriers $\widehat{H}_p(m)$ and $\widehat{H}_p(m+1)$ can be given by

$$\widehat{H}(mV+u) = \widehat{H}_p(m) + \left(\widehat{H}_p(m+1) - \widehat{H}_p(k)\right)\left(\frac{u}{V}\right), \quad (0 \le u \le V). \tag{13}$$

In order to combat the phase and amplitude distortions caused by the fiber channel on the subchannels, a one-tap zero forcing (ZF) equalizer is employed on the received

OFDM signal R. The one-tap equalizer is simply realized by multiplying each individual subcarrier with the complex value of the equalizer, which is to be computed based on its own subcarrier channel coefficient. In the sequel, the output of the equalizer can be written as

$$\widehat{X} = GR, \tag{14}$$

where

$$G = \begin{bmatrix} G_{0,0} & 0 & \cdots & 0 \\ 0 & G_{1,1} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & G_{N,N} \end{bmatrix}, \tag{15}$$

where $G_{0,0} = 1/H_n$ and H_n is the nth frequency channel coefficient. After removing the Hermitian symmetric part of the signal vector $\widehat{X}$, the new signal vector $\widehat{Y}$ of size D is obtained. Then vector $\widehat{Y}$ is transformed by the inverse precoding matrix F^H. Then the original data signal can be estimated as $\widehat{S} = F^H \widehat{Y}$.

The lth element of $\widehat{S}$ can be calculated as

$$\widehat{S}_l = a_l \sum_{d=0}^{D-1} \widehat{Y}_d \cos\left[\frac{\pi(2d+1)l}{2D}\right], \quad l = 0, 1, \ldots, D-1, \tag{16}$$

where the definition of a_l is the same as a_l in (3).

In our proposed scheme, the scaling is operated at the transmitter and the receiver does not need any knowledge about the scaling factor. The scaling factor can be estimated by channel estimation technique at the receiver. Thus, no extra operation is required at the receiver [19].

2.2. Scaling Technique. Due to the application of DCT precoding, the PAPR of the transmitted signals is significantly reduced. Thus, the amplitude range of the DCT precoded OFDM signal is much less than that of the original OFDM signal. For improving performance of DCT precoded OFDM system, a scaling technique is employed in a DCT precoded OFDM system to fully exploit the dynamic range of a DAC.

For a time domain original OFDM symbol $\{x_n, n = 0, 1, \ldots, N-1\}$, let us denote the maximum and minimum of the symbol by $A_{\max}$ and $B_{\min}$, respectively. For a time domain DCT precoded OFDM symbol $\{x_n, n = 0, 1, \ldots, N-1\}$, let us denote the maximum and minimum amplitude value of the symbol by $a_{\max}$ and $b_{\min}$, respectively. Due to the application of the DCT precoding, the absolute of amplitude value of DCT precoded OFDM signal is lower than that of the original OFDM signal. So the absolute values of $a_{\max}$ and $b_{\min}$ are smaller than those of $A_{\max}$ and $B_{\min}$, respectively. Furthermore to improve the performance of system, we employ a scaling factor before DAC and after IFFT. The scaling factor is given by

$$\beta = \frac{A_{\max} - B_{\min}}{a_{\max} - b_{\min}}. \tag{17}$$

The scaled signal fully exploits the dynamic range of DAC without changing the transmitter structure. Then the scaled DCT precoded OFDM signal can be expressed as

$$z_n = \beta \cdot x_n, \tag{18}$$

where $\beta \geq 1$. After scaling, the maximum amplitude value of the DCT precoded OFDM is the same as that of the original OFDM.

2.3. BER Performance Analysis. To study the BER performance of the DCT precoded IM/DD optical OFDM system with scaling, this section will illustrate the performance analysis of the conventional OFDM, conventional DCT precoded OFDM, and scaled DCT precoded OFDM systems across two different channels, such as AWGN and frequency-selective fading, with M-QAM data mapping. For the M-QAM scheme, the theoretical BER expression of OFDM over AWGN channel is given as [21]

$$P_{b,\mathrm{AWGN}}^{\mathrm{original}} = \left(\frac{4 - 2^{(2-m/2)}}{m}\right) Q\left(\sqrt{\frac{3\gamma_0}{(M-1)}}\right), \tag{19}$$

where $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-t^2/2} dt$ denotes the Q function, $m = \log_2 M$ is the number of bits per constellation point, and γ_0 is the signal-to-noise ratio (SNR) at the receiver.

2.3.1. BER Performance Analysis in AWGN Channel. Basically, the performance of original OFDM systems is the same as that of conventional DCT precoded OFDM systems over AWGN channel [21]. The BER can be calculated according to (19). However, when the proposed scaling is employed in a DCT precoded OFDM system the SNR at the receiver can be improved.

The effective SNR of the proposed scaling scheme can be expressed as

$$\gamma = \frac{\beta^2 \sigma_X^2}{\sigma_{\mathrm{AWGN}}^2} = \beta^2 \gamma_0. \tag{20}$$

Thus the BER of the proposed scaling scheme can be expressed as [21]

$$P_{b,\mathrm{AWGN}}^{\mathrm{scaling}} = \left(\frac{4 - 2^{(2-m/2)}}{m}\right) Q\left(\sqrt{\frac{3\beta^2\gamma_0}{(M-1)}}\right). \tag{21}$$

Comparing (19) and (21), it is clear that the value of $P_{b,\mathrm{AWGN}}^{\mathrm{scaling}}$ is smaller than that of $P_{b,\mathrm{AWGN}}^{\mathrm{original}}$ due to $0 \leq \beta \leq 1$. So the proposed scaling can improve the BER performance of conventional DCT precoded OFDM systems in AWGN channel.

2.3.2. BER Performance Analysis in Dispersive Fiber Channel. Similar to the analysis in [22], when PMD is absent and group-velocity dispersion (GVD) is the only fiber impairment considered, we can express the transfer function of the fiber as

$$H(\omega) = \exp\left(j\omega^2 \frac{\beta_2}{2} L\right), \tag{22}$$

where β_2 is the fiber GVD parameter and L is the fiber length. β_2 can be defined as $\beta_2 = -D\lambda^2/2\pi c$. The impulse response $h(t)$ can be given by the inverse Fourier transform of (22).

Dispersive fiber channel $h(t)$ can be described using a linear time invariant (LTI) transfer function [22]. For DC-OFDM system, the transmitted symbols are modulated such that the time domain waveform is real. Thus, the equivalent linear channel of fiber can be written as

$$h_{\text{eq}}(t) = \frac{h(t) + h^*(t)}{2}. \tag{23}$$

In this work, we mainly research the effect of the scaling scheme on the BER of system, so without loss of generality, we do not consider impact of the nonlinear DFB LD and PD detection component. At the receiver, the receiver signal can be expressed as

$$r(t) = x(t) * h(t) + n(t), \tag{24}$$

where $x(t)$, $r(t)$, and $n(t)$ are the transmitted OFDM signal, the received OFDM signal, and the AWGN noise.

Let H_k be the N-point DFT of $h_{\text{eq}}(t)$. The set of data-carrying subcarriers for the DCT precoded IM/DD optical OFDM is $\kappa = \{1, 2, \ldots, N/2 - 1\}$ and $|\kappa_d| = N/2 - 1 = D$. With equalization in receiver end, the overall transmission system is equivalent to D parallel AWGN channels [23]. For a frequency-selective (FS) channel, the SNR of every subcarrier channel γ_k can be expressed as

$$\gamma_k = \gamma_0 \left|H_k\right|^2. \tag{25}$$

Thus, the BER performance of the original OFDM system can be expressed as

$$P_{b,\text{FS}}^{\text{original}} = \frac{1}{D}\sum_{k\in\kappa}\left(\frac{4 - 2^{(2-m/2)}}{m}\right) Q\left(\sqrt{\frac{3\gamma_0 \left|H_k\right|^2}{(M-1)}}\right). \tag{26}$$

The BER analysis of the precoded OFDM system has been given in literature [15]. For the DCT precoded optical OFDM system, the SNR of the lth subcarrier channel can be expressed as [15]

$$\gamma_l^{\text{DCT}} = \frac{\gamma_0}{\sum_{d=0}^{D-1}\left|F_{l,d}\right|^2 \left|H_d\right|^{-2}}, \quad 0 \le d, l \le D - 1. \tag{27}$$

Hence, the BER of a DCT precoded system with ZF equalizer is

$$P_{b,\text{FS}}^{\text{DCT}} = \frac{1}{D}\sum_{l\in\kappa}\left(\frac{4 - 2^{(2-m/2)}}{m}\right) Q\left(\sqrt{\frac{3\gamma_l^{\text{DCT}}}{(M-1)}}\right). \tag{28}$$

We can see from (27) that the same amount of noise is distributed among the subcarrier channels based on DCT precoded OFDM system. Thus the BER performance of the DCT precoded OFDM system can be improved compared with that of the original optical OFDM system.

For the scaled DCT precoded OFDM system, the SNR of the lth subcarrier channel can be expressed as

$$\gamma_l^{\text{scaling,DCT}} = \frac{\beta^2 \gamma_0}{\sum_{d=0}^{D-1}\left|F_{l,d}\right|^2 \left|H_d\right|^{-2}}, \quad 0 \le k, l \le D - 1. \tag{29}$$

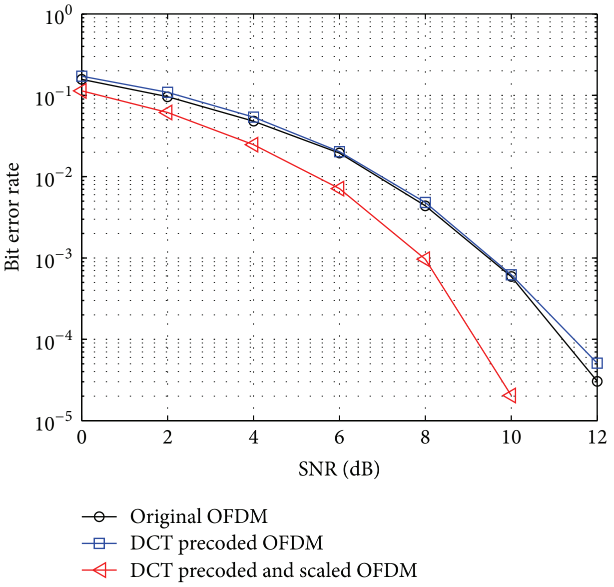


Figure 2: BER performance comparison over AWGN channel.

The BER of a DCT precoded and scaled system with ZF equalizer can be expressed as

$$\begin{aligned} & P_{b,\text{FS}}^{\text{scaling,DCT}} \\ & \quad = \frac{1}{D}\sum_{k\in\kappa}\left(\frac{4 - 2^{(2-m/2)}}{m}\right) Q\left(\sqrt{\frac{3\beta^2\gamma_l^{\text{DCT}}}{(M-1)}}\right). \end{aligned} \tag{30}$$

Comparing (28) to (30), it is clear that scaling can also improve the BER of the conventional DCT precoded OFDM system in dispersive fiber channel.

2.3.3. Simulation Results. We first study the BER performance of a system with scaling scheme in an AWGN channel by simulation. In the simulation setup, we use the IEEE 802.16-2004 standard [24] as the PHY protocol. The OFDM frame structure has 192 data subcarriers and eight pilot tones for channel estimation and equalization, 56 unused tones for the guard band, and 64 tones for the CP.

Figure 2 shows the BER performance versus the SNR for the QPSK transmission of the proposed DCT precoded and scaled OFDM scheme in an AWGN channel. In the simulation, the bit rate is 5 Gbits/s. From Figure 2 we can see that the scaling scheme can improve the BER performance of the DCT precoded and scaled OFDM compared with the conventional DCT precoded OFDM. We can see that there is no significant difference between the original OFDM and conventional DCT precoded OFDM. The simulation results are consistent with the previous analysis and reported results [25].

Next, we investigate the BER performance of the DCT precoded and scaled OFDM over single-mode fiber channel by simulation. The frequency response of the optical fiber channel as expressed in (22) is employed. The summary of key simulation parameters is given in Table 1.

TABLE 1: Simulation parameters.

λ	1550 nm
D	17 ps/(nm km)
Rb	5 Gbits/s
Modulation	QPSK
FFT size	256
Number of pilot data	8
Length of CP	32
L (length of fiber)	100 and 200 km

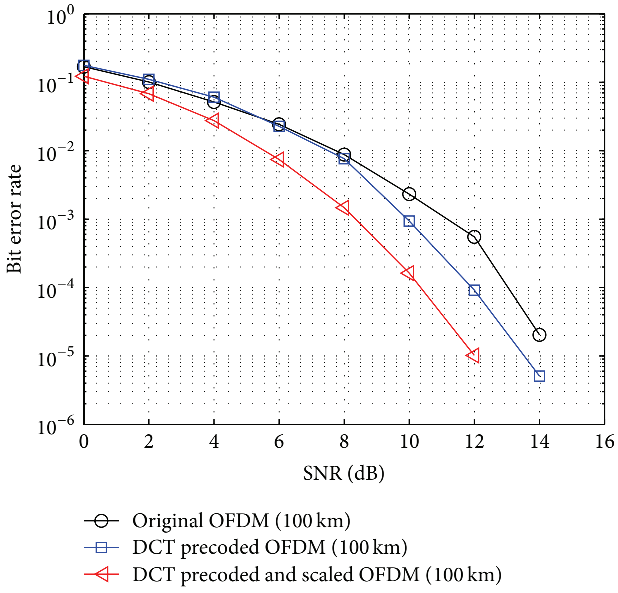


FIGURE 3: BER performance comparison over 100 km fiber channel.

Figure 3 shows the BER performance versus the SNR for the QPSK transmission of the proposed precoding scheme over 100 km single-mode fiber channel. Form Figure 3, we can see that the proposed scaling scheme can improve the BER of system compared with the conventional DCT precoded OFDM system. At BER = 10^{-3}, the scaling scheme can obtain approximately 1.6, 3 dB gain compared with the conventional DCT precoded OFDM and original OFDM, respectively.

Figure 4 shows the BER performance comparison of systems when the length of fiber is set at 200 km. At BER = 10^{-3}, the scaling scheme can obtain approximately 2, 3.5 dB gain compared with the conventional DCT precoded OFDM and original OFDM, respectively. From Figures 3 and 4, we can see that the BER performances of systems with 100 km fiber length case are better than those of system with 200 km fiber length.

3. Experimental Setup

Figure 5 shows the optical OFDM transmission experimental setup for DCT precoded and scaled OFDM transmission scheme. In the experiment, three types of OFDM signals are used: 4 Gs/s (2.7 Gbits/s) original OFDM, DCT precoded OFDM, and DCT precoded and scaled OFDM. The OFDM signals are generated offline by the MATLAB program. An OFDM frame is composed of a training sequence (TS) and 512 data-carrying OFDM symbols. The TS is used as symbols synchronization and channel estimation. The size of IFFT (FFT) is 256. Among the 256 subcarriers, 192 (96 $*$ 2) data subcarriers are used for the data, 8 are pilot subcarriers, and 56 subcarriers are set to zero as the guard interval. And among the 192 subcarriers, 96 subcarriers are used to transmit effective data in the positive frequency bins. The other corresponding 96 subcarriers in the negative frequency bins are filled with Hermitian symmetric data to generate real-valued OFDM signal. The length of cyclic prefix is 32 samples. The QPSK OFDM signal is first generated in MATLAB and uploaded onto an arbitrary waveform generator (AWG) through DAC. The AWG was operated with 4 Gs/s and a resolution of 8 bits. The peak-to-peak amplitude of the electrical OFDM is 1 volt. The data rate was 4 Gs/s $*$ 192/2/256 $*$ 256/(256 + 32) $*$ 2 (bits/symbol for QPSK) = 2.7 Gbits/s. The central wavelength of the continuous light wave (CW) generated by a DFB is 1549.261 nm. A Mach-Zehnder modulator (MZM) biased at 2.2 v is used for direct up conversion to optical domain. Then the optical signal at the MZM output is amplified by an erbium-doped fiber amplifier (EDFA) and launched into a 100 km standard single-mode fiber (SSMF). The attenuation and dispersion coefficients of the fiber are 0.19 dB/km and 17 ps/(nm km), respectively.

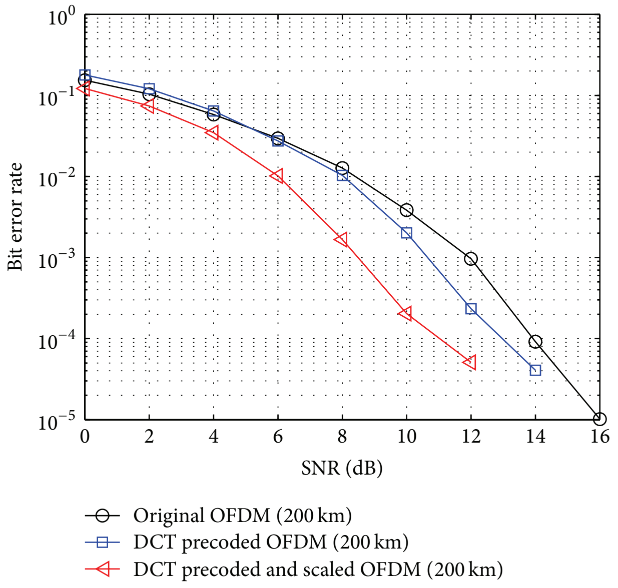


FIGURE 4: BER performance comparison over 200 km fiber channel.

At the receiver, the received optical power is controlled by a tunable attenuation (ATT). After that the transmitted optical OFDM signal is transformed into an electrical domain OFDM signal by a PD detector. Further, the electrical signal is captured by a Tektronix TDS684B real-time oscilloscope. The MATLAB program is used to demodulate the waveform data, which are recorded by a real-time oscilloscope.

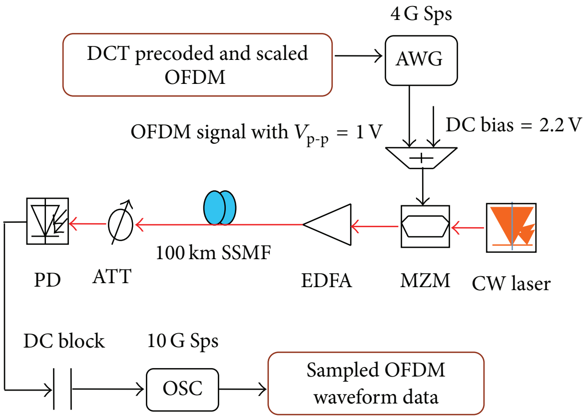


FIGURE 5: Experimental setup (EDFA: erbium-doped fiber amplifier; ATT: attenuator; PD: photodiode; OSC: oscilloscope).

4. Results and Discussion

4.1. PAPR of DCT Precoded OFDM Signals. PAPR is defined as the ratio between the maximum peak power and the average power of the transmitted OFDM signals. The PAPR of the OFDM signal x_n is given by

$$\text{PAPR} = \frac{\max_{0\leq n\leq N-1}\left[\left|x_n\right|^2\right]}{E\left\{\left|x_n\right|^2\right\}}. \tag{31}$$

Reducing $\max[|x_n|]$ is the principle goal of PAPR reduction techniques. The precoding technique reduces the PAPR of OFDM signals without changing the average power of the original OFDM signal.

The PAPR performance of OFDM signal can be evaluated using the complementary cumulative distribution function (CCDF). The CCDF of PAPR (namely, P_c) can be expressed as $P_c = P\{\text{PAPR} > \text{PAPR0}\}$, where P_c indicates the probability that PAPR exceeds a particular value PAPR0.

However, due to the fact that the all-sample value of the DCT precoded OFDM signal is multiplied by a scaling factor β, according to definition equation (31), the PAPR of scaled DCT precoded OFDM is the same as that of the conventional DCT precoded OFDM. The PAPR performance of the OFDM system can be evaluated using the complementary cumulative distribution function (CCDF). Figure 6 shows the CCDF comparisons of a QPSK signal of 50000 OFDM frames. We observe that, at CCDF = 10^{-3}, the PAPR of the DCT precoded QPSK OFDM signals may be reduced by 1.3 dB, compared to the original QPSK OFDM signals.

In our experiment setup, the OFDM data signals are produced by MATLAB program. Figures 7 and 8 show the temporal waveforms of original OFDM and DCT precoded OFDM, respectively. We observe that the DCT precoded OFDM signal fluctuates less than the original OFDM signal. The maximum amplitude value and minimum amplitude vale of original OFDM signal are 3.8588 and −3.5954, respectively, while the maximum amplitude and minimum amplitude of DCT precoded OFDM signal are 3.5133 and −3.4457, respectively.

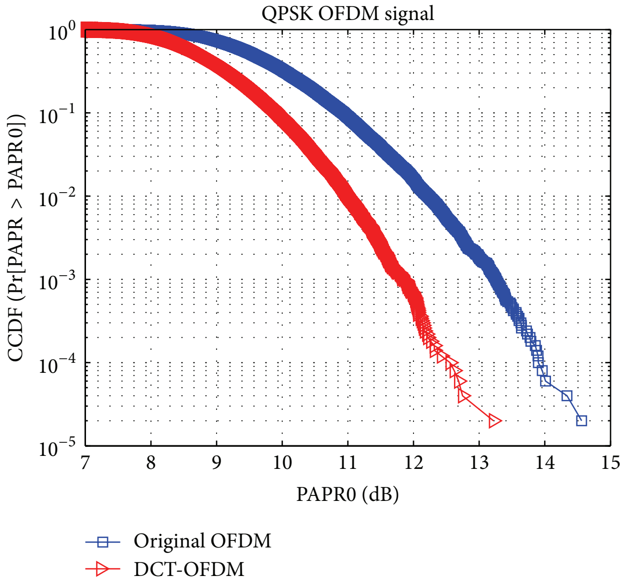


FIGURE 6: Comparison of the PAPRs of the OFDM signals.

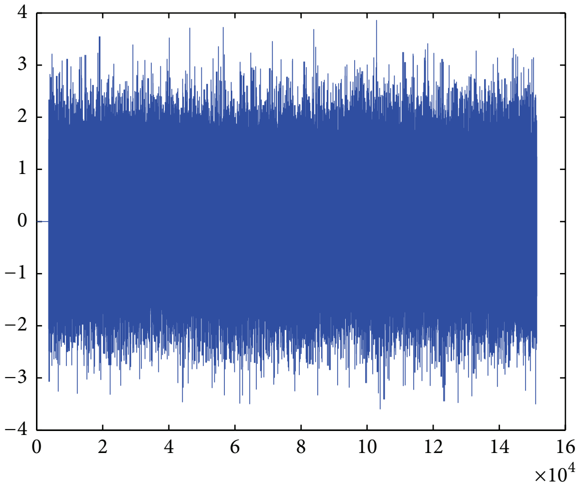


FIGURE 7: Temporal waveform of the original QPSK OFDM signal.

For improving the system BER performance we employed scaling to the conventional DCT precoded OFDM system. In following experiment, the scaling factor of the DCT precoded OFDM can be calculated by

$$\beta = \frac{A_{\max} - B_{\min}}{a_{\max} - b_{\min}} = \frac{3.8588 - (-3.5954)}{3.5133 - (-3.4457)} \approx 1.1. \tag{32}$$

Thus, the scaled DCT precoded OFDM is be amplified by 1.1 times compared to the conventional DCT precoded OFDM.

Figure 9 shows the temporal waveform of DCT precoded and scaled OFDM signal. After scaling, the maximum amplitude of the precoded and scaled OFDM signal is the same as that of the original OFDM signal. In following experiment, the generated OFDM signal is downloaded to an arbitrary waveform (AWG) and normalized. The normalized OFDM signal has a peak-to-peak value of 1 volt.

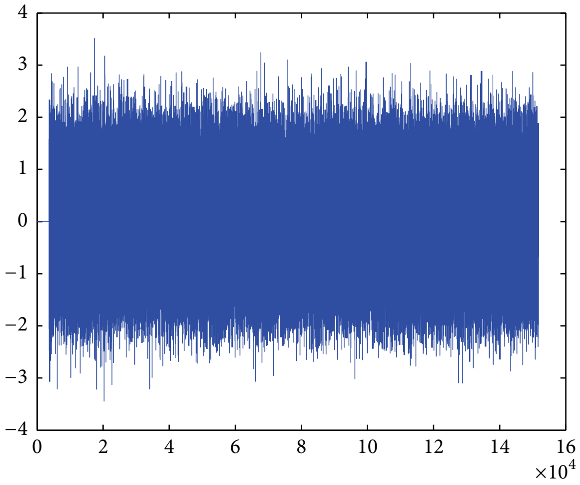


FIGURE 8: Temporal waveform of the conventional DCT precoded QPSK OFDM signal.

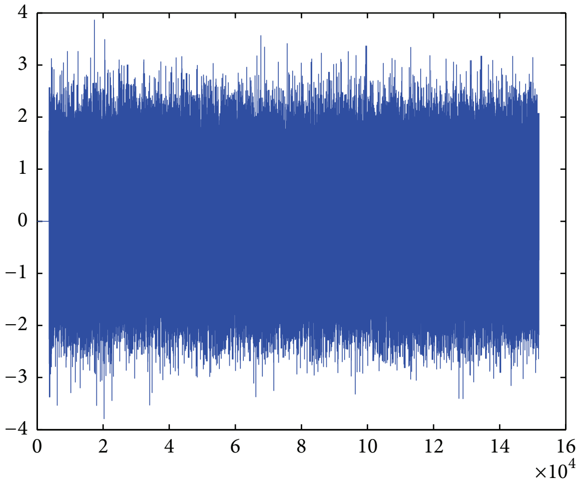


FIGURE 9: Temporal waveform of the DCT precoded and scaled QPSK OFDM signal.

4.2. BER Performance. The BER performance of the proposed scaling scheme has been evaluated by practical experiment platform in this section. For comparison BER performance, we have measured the BER of the original OFDM, conventional DCT precoded OFDM, and DCT precoded OFDM with scaling. Figure 10 shows the measured BER performance results of the DCT precoded and scaled QPSK OFDM signal, conventional precoded QPSK OFDM signal, and original QPSK OFDM signal at a fixed sample rate of 4 Gs/s with the launch optical power of 6 dBm. We can see that the performance of the DCT precoded and scaled system is better than that of the conventional DCT precoded OFDM and the original OFDM. It can be seen that the received sensitivity of DCT precoded and scaled OFDM signal at the BER of 10^{-3} after 100 km SMF transmission can be improved by about 3 dB compared to the original OFDM signals and by 1.3 dB compared to the conventional DCT precoded OFDM signals.

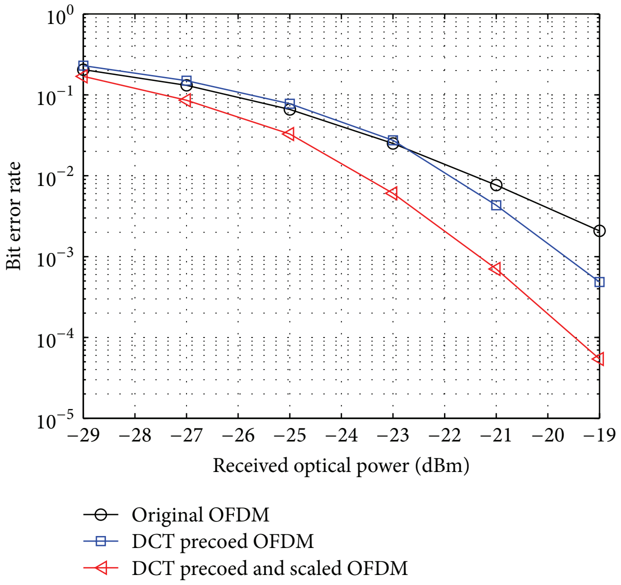


FIGURE 10: Measured BER versus received optical power.

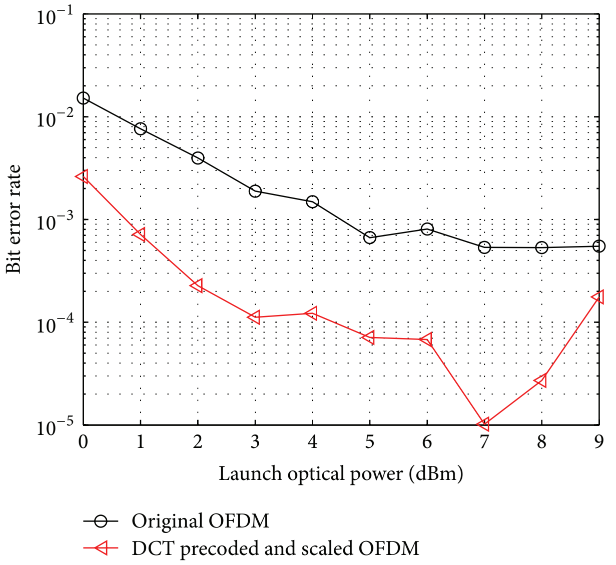


FIGURE 11: Measure BER versus launched optical power.

Figure 11 shows the measured BER performance comparisons of the DCT precoded and scaled QPSK OFDM signals and conventional QPSK OFDM signals across different launch optical powers. The received optical power is fixed at −19 dBm. From Figure 11 we can see that the BER performance of the DCT precoded and scaled scheme is better than that of the original OFDM signals at the different launch optical power. When the received optical power of the receiver is lower the 7 dBm, the sensitivity of the received signal is increased with the increase of the launch optical power. When the received optical power of the receiver is higher the 7 dBm, the sensitivity of the received signal is decreased with the increase of the launch optical power due to the impact of fiber nonlinearity.

5. Conclusion

We have proposed a scaling scheme for a DCT precoded IM/DD optical OFDM system. This scheme can fully exploit the dynamic range of a DAC and significantly improve the BER performance of systems. The advantage of this scaling technique is that it does not require adding and hardware device to the system. We have experimentally researched the BER performance of a DCT precoded IM/DD optical OFDM system with scaling in practical transmission experimental system. The experimental results show that the received sensitivity at a BER of 10^{-3} for a 4 Gs/s DCT precoded and scaled OFDM signal and after 100 km standard single-mode fiber transmission has been improved by 3 dB when compared with the original OFDM systems in the SMF link and by 1.3 dB when compared with the conventional DCT precoded OFDM signals. Thus, the proposed scaling technique can be used for optical communication system design.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors would like to thank Professor Lin Chen for his supervision and providing the experimental test equipment. The authors would like to thank Dr. Ming Chen for his finishing of the experimental data acquisition. This work was supported in part by the Open Fund of the State Key Laboratory of Millimeter Waves (Southeast University, Ministry of Education, China) under Grant K201214, by the Zhejiang Provincial Natural Science Foundation of China under Grant LY13F050005, and by the National Natural Science Foundation of China under Grants 61379027 and 61505176.

References

[1] I. Kaminow and T. Y. Li, *Optical Fiber Telecommunications IVB*, Academic Press, New York, NY, USA, 2002.

[2] E. Vanin, "Performance evaluation of intensity modulated optical OFDM system with digital baseband distortion," *Optics Express*, vol. 19, no. 5, pp. 4280–4293, 2011.

[3] J. Armstrong and B. J. C. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE Communications Letters*, vol. 12, no. 5, pp. 343–345, 2008.

[4] Z.-P. Wang, J.-N. Xiao, F. Li, and L. Chen, "Hadamard precoding for PAPR reduction in optical direct detection OFDM systems," *Optoelectronics Letters*, vol. 7, no. 5, pp. 363–366, 2011.

[5] L. Tao, J. Yu, Y. Fang, J. Zhang, Y. Shao, and N. Chi, "Analysis of noise spread in optical DFT-S OFDM systems," *Journal of Lightwave Technology*, vol. 30, no. 20, Article ID 6298919, pp. 3219–3225, 2012.

[6] Q. Yang, Z. He, Z. Yang, S. Yu, X. Yi, and W. Shieh, "Coherent optical DFT-spread OFDM transmission using orthogonal band multiplexing," *Optics Express*, vol. 20, no. 3, pp. 2379–2385, 2012.

[7] J. Xiao, J. Yu, X. Li et al., "Hadamard transform combined with companding transform technique for PAPR reduction in an optical direct-detection OFDM system," *Journal of Optical Communications and Networking*, vol. 4, no. 10, pp. 709–714, 2012.

[8] W. Li, S. Yu, W. Qiu, J. Zhang, Y. Lu, and W. Gu, "FWM mitigation based on serial correlation reduction by partial transmit sequence in coherent optical OFDM systems," *Optics Communications*, vol. 282, no. 18, pp. 3676–3679, 2009.

[9] R. Luo, R. Li, Y. Dang, J. Yang, and W. Liu, "Two improved SLM methods for PAPR and BER reduction in OFDM-ROF systems," *Optical Fiber Technology*, vol. 21, pp. 26–33, 2015.

[10] B. Goebel, S. Hellerbrand, and N. Hanik, "Link-aware precoding for nonlinear optical OFDM transmission," in *Proceedings of the Conference on Optical Fiber Communication (OFC '10)*, pp. 1–3, IEEE, San Diego, Calif, USA, March 2010.

[11] Y. Gao, J. Yu, J. Xiao, Z. Cao, F. Li, and L. Chen, "Direct-detection optical OFDM transmission system with pre-emphasis technique," *Journal of Lightwave Technology*, vol. 29, no. 14, Article ID 5766004, pp. 2138–2145, 2011.

[12] S. Kang, J. Lee, and J. Jeong, "PAPR reductin technique by inserting a power-concentrated subcarrier for CO-OFDM," *Optics Communications*, vol. 350, pp. 119–123, 2015.

[13] M.-J. Hao and C.-H. Lai, "Precoding for PAPR reduction of OFDM signals with minimum error probability," *IEEE Transactions on Broadcasting*, vol. 56, no. 1, pp. 120–128, 2010.

[14] S. Adhikari, S. Jansen, M. Kuschnerov, B. Inan, M. Bohn, and W. Rosenkranz, "Investigation of spectrally shaped DFTS-OFDM for long haul transmission," *Optics Express*, vol. 20, no. 26, pp. B608–B614, 2012.

[15] Y.-P. Lin and S.-M. Phoong, "BER minimized OFDM systems with channel independent precoders," *IEEE Transactions on Signal Processing*, vol. 51, no. 9, pp. 2369–2380, 2003.

[16] B. Ranjha and M. Kavehrad, "Precoding techniques for PAPR reduction in asymmetrically clipped OFDM based optical wireless system," in *Broadband Access Communication Technologies VII*, vol. 8645 of *Proceedings of SPIE*, International Society for Optics and Photonics, San Francisco, Calif, USA, January 2013.

[17] M. Sung, J. Lee, and J. Jeong, "DCT-precoding technique in optical fast OFDM for Mitigating fiber nonlinearity," *IEEE Photonics Technology Letters*, vol. 25, no. 22, pp. 2209–2212, 2013.

[18] Z.-P. Wang, S.-F. Chen, Y. Zhou, M. Chen, J. Tang, and L. Chen, "Combining discrete cosine transform with clipping for PAPR reduction in intensity-modulated OFDM systems," *Optoelectronics Letters*, vol. 10, no. 5, pp. 356–359, 2014.

[19] Z. Wang, Q. Wang, S. Chen, and L. Hanzo, "An adaptive scaling and biasing scheme for OFDM-based visible light communication systems," *Optics Express*, vol. 22, no. 10, pp. 12707–12715, 2014.

[20] T. Komine, J. H. Lee, S. Haruyama, and M. Nakagawa, "Adaptive equalization system for visible light wireless communication utilizing multiple white led lighting equipment," *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 2892–2900, 2009.

[21] S.-H. Wang, C.-P. Li, K.-C. Lee, and H.-J. Su, "A novel low-complexity precoded OFDM system with reduced PAPR," *IEEE Transactions on Signal Processing*, vol. 63, no. 6, pp. 1366–1376, 2015.

[22] D. J. F. Barros and J. M. Kahn, "Comparison of orthogonal frequency-division multiplexing and on-off keying in amplified direct-detection single-mode fiber systems," *Journal of Lightwave Technology*, vol. 28, no. 12, Article ID 5456211, pp. 1811–1820, 2010.

[23] P. Saengudomlert, "On the benefits of pre-equalization for ACO-OFDM and flip-OFDM indoor wireless optical transmissions over dispersive channels," *Journal of Lightwave Technology*, vol. 32, no. 1, pp. 70–80, 2014.

[24] IEEE standard for local and metropolitan area network, part 16: air interface for fixed broadband wireless access systems, IEEE Standard 802.16-2004.

[25] X. Zhu, G. Zhu, and T. Jiang, "Reducing the peak-to-average power ratio using unitary matrix transformation," *IET Communications*, vol. 3, no. 2, pp. 161–171, 2009.

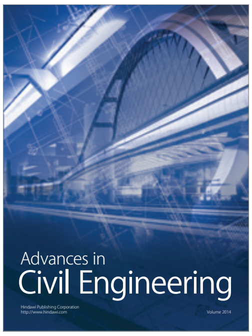

Journal of
Engineering


The Scientific World Journal

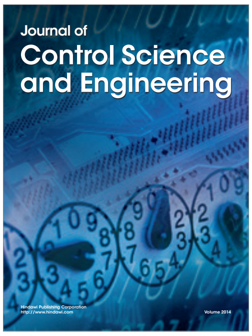

International Journal of
Rotating Machinery


Journal of
Sensors

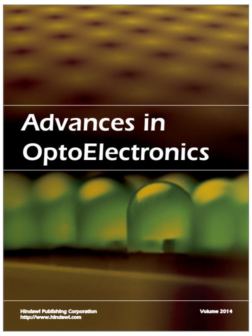

International Journal of
Distributed Sensor Networks


Advances in
Civil Engineering


Journal of
Robotics

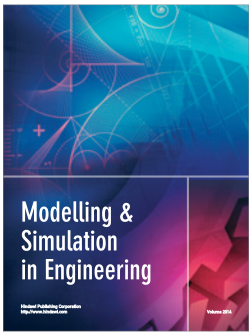

Journal of
Control Science and Engineering


Journal of
Electrical and Computer Engineering

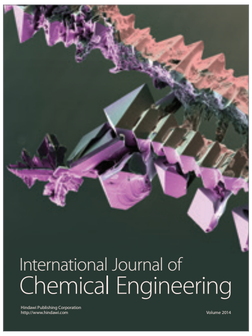

Advances in
OptoElectronics

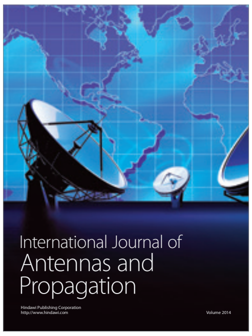

VLSI Design


International Journal of
Navigation and Observation

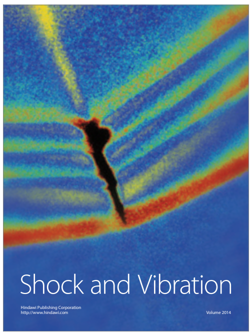

Modelling & Simulation in Engineering

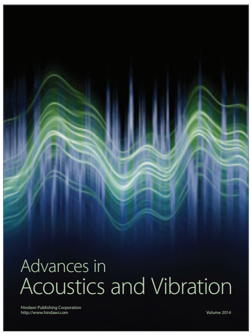

International Journal of
Aerospace Engineering


International Journal of
Chemical Engineering


International Journal of
Antennas and Propagation


Active and Passive
Electronic Components


Shock and Vibration


Advances in
Acoustics and Vibration