Carrier-Interferometry-OFDM for Nonlinear Tolerance Improvement in Optical Systems with Direct Detection

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Abstract

In this paper, carrier-interferometry orthogonal frequency division multiplexing (CI-OFDM) technique is applied with direct detection optical OFDM (DD-OFDM) for peak-to-average power ratio (PAPR) reduction. We compare by simulation the performance of a CI-DD-OFDM system with that of conventional DD-OFDM. CI-OFDM reduces the PAPR; this in turn improves the nonlinear tolerance in optical-OFDM systems. 4-QAM and 16-QAM modulation formats are considered here for a single channel and 5 channels WDM transmissions. Noise performance comparisons have been investigated with back-to-back (B2B) transmission; the results show that for CI-DD-OFDM the OSNR is improved by ~ 1 dB and < 0.5 dB for 4-QAM and 16-QAM, respectively. For nonlinearity comparisons with single channel, the CI-DD-OFDM system Q-value with 4-QAM is improved by ~ 3 dB and ~ 2 dB for 80 km and 800 km transmissions, respectively, while for 16-QAM it is improved by ~ 2 dB and ~ 1 dB for 80 km and 800 km transmissions, respectively. For nonlinearity comparisons with 5 WDM channels, the CI-DD-OFDM system Q-value with 4-QAM is improved by ~ 1.6 dB and ~ 1 dB for 80 km and 800 km transmissions, respectively, while for 16-QAM it is improved by ~ 1.2 dB and ~ 0.8 dB for 80 km and 800 km transmissions, respectively. Thus, the CI-DD-OFDM system outperforms the conventional DD-OFDM in terms of nonlinearity tolerance.

1 Introduction

In order to meet the ever-growing demand for In order to meet the ever-growing demand for transmission capacity, techniques originally known from classical digital communications have entered the field of optical communications, such as orthogonal frequency division multiplexing (OFDM). Optical transmission systems employing OFDM have gained considerable research interest because OFDM can combat fiber chromatic dispersion and has the capability to use higher level modulation formats to increase spectral efficiency [1]-[3].

Despite the benefits of OFDM, one of the most serious problems with OFDM is that an OFDM time signal exhibits high PAPR. The problem of high PAPR in OFDM requires RF-amplifiers, digital-to-analog (DAC) converter (limited resolution) and optical modulator with large dynamic range (linear region) to avoid distortions due to the nonlinear characteristics of such devices. In addition, high PAPR degrades the system's tolerance to nonlinear impairments of the fiber channel. Several PAPR reduction techniques have been proposed, one of these techniques is the CI-OFDM technique.

In this paper, we apply CI-OFDM technique, the concept of which is explained in the next chapter, for PAPR reduction. CI-OFDM enhances the system performance *without sacrificing bandwidth or data rate*. We compare the performance of a CI-OFDM system with that of conventional OFDM. Simulation results show that CI-OFDM outperforms conventional OFDM for both 4-QAM and 16-QAM in single channel (standard single mode fiber SSMF) and WDM transmissions.

2 Concept of CI-OFDM

CI-OFDM has been widely studied in wireless communication as one of several PAPR reduction techniques [4], [5]. In CI-OFDM, each information symbol is transmitted simultaneously over all the subcarriers by using orthogonal CI spreading code. **Fig. 1** shows the transmitter and receiver architectures of a CI-OFDM system. The spreading code for the k^{th} OFDM symbol is

$$C\left(k\right)=\{e^{j0\cdot\theta(k)},e^{j1\cdot\theta(k)},\cdots,e^{j(N-1)\theta(k)}\},\quad k=0\cdots N-1, \quad (1)$$

where $\theta(k)=2\pi k/N$. The k^{th} information symbol, $a(k)$, is spread into N components through the spreading code $C(k)$, and the equivalent symbols that are fed into the IFFT transformer can be expressed as

$$S\left(i\right)=\sum_{k=0}^{N-1}a\left(k\right)\cdot e^{j\frac{2\pi}{N}ik},\quad i,k=0,1,\cdots,N-1\cdot \qquad (2)$$

Note that CI-OFDM is similar to DFT-spread OFDM [6], where each transmitted symbol is spread over all the subcarriers. However, CI-OFDM has the following advantages: (1) in DFT-spread OFDM only the DFT code can be used as a spreading code, while in a CI-OFDM high number of orthogonal spreading codes can be used from which an optimum code for optimum PAPR mini-

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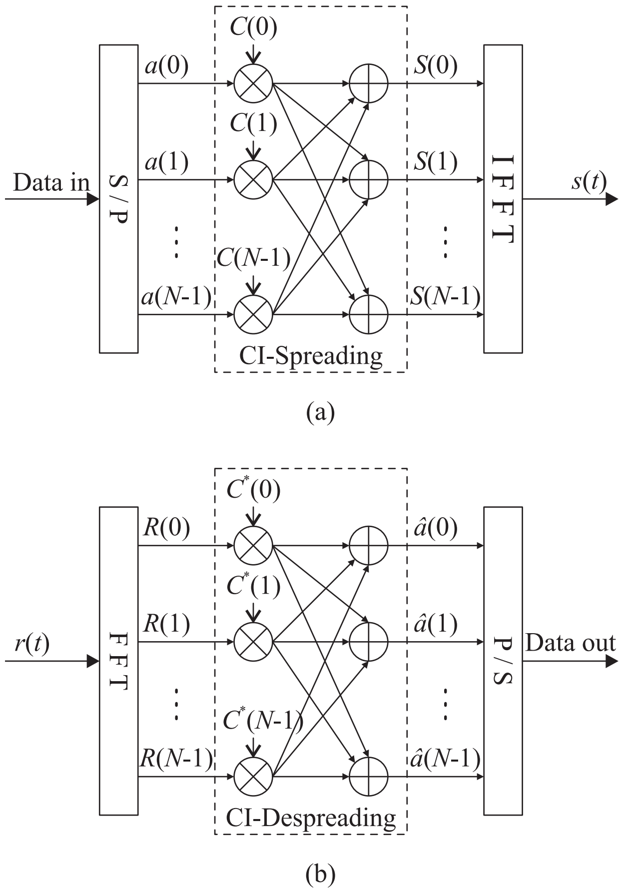

Fig.1 CI-OFDM architecture: (a) Transmitter and (b) Receiver

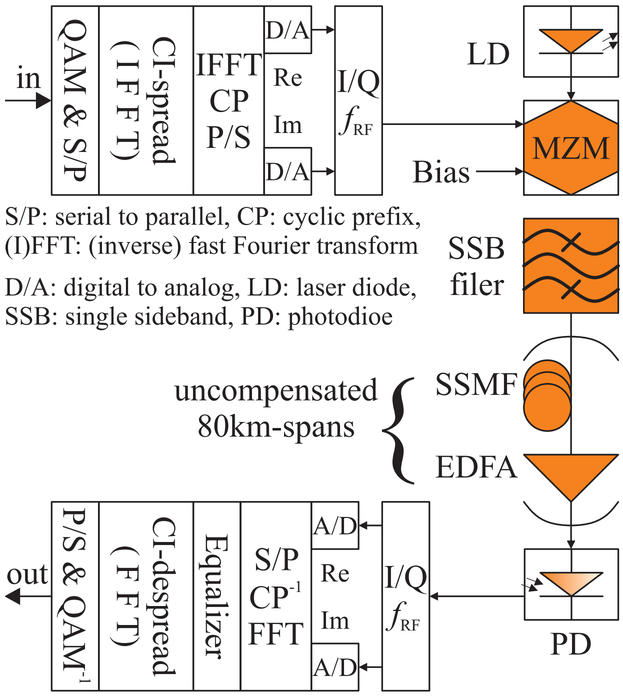

Fig.2 Direct detection CI-OFDM system block diagram.

mization can be selected, (2) in DFT-spread OFDM the number of subcarriers is limited to $N = 2^m$ (i.e. N is a power of 2 constraint), while in CI-OFDM orthogonal CI codes can be defined for any number of subcarriers, which makes CI-OFDM more flexible than DFT-spread OFDM.

For subcarrier separation of $\Delta f = 1/T$, where T is the OFDM symbol duration, the baseband CI-OFDM signal is

$$s(t)=\sum_{k=0}^{N-1}\sum_{i=0}^{N-1} a(k)\cdot e^{j2\pi i\Delta f t}\cdot e^{j\frac{2\pi}{N}ki}. \qquad (3)$$

For $N = 2^m$ (i.e. N is power of 2), the transmitter and the receiver can be implemented by performing IFFT and FFT twice, respectively. This in turn reduces the system complexity compared to other PAPR reduction techniques.

3 Direct detection CI-OFDM system setup

The DD-CI-OFDM system setup is shown in **Fig. 2**. After serial to parallel (S/P) conversion and M-QAM mapping, the complex symbols are fed into the CI-spreading of size $N = 512$ components which is here equal to the data carrying N subcarriers of the IFFT block. The IFFT performs the OFDM modulation, which is followed by the insertion of cyclic prefix (CP) and parallel to serial (P/S) conversion. The real valued, up-converted to intermediate frequency f_{RF} OFDM signal is generated by using an electrical I/Q modulator. The resulting signal has to be biased for driving an external optical MZM in order to achieve sufficient carrier power for direct detection. A single-sideband (SSB) optical filter is used to transmit only one sideband together with the optical carrier.

The optical transmission line consists of spans of 80 km of SSMF each without dispersion compensating fiber (DCF). The fiber has a dispersion of 17 ps/nm/km, a loss of 0.2 dB/km, a nonlinear refractive index of 3.2×10^{-20} m^2/W and an effective core area of 8×10^{-11} m^2. Span loss of 16 dB is compensated for by means of inline noiseless optical amplifiers, as noise only limits the signal quality at low input powers [7]. An Erbium Doped Fiber Amplifier (EDFA), with noise figure of 5 dB for noise loading, is applied as a preamplifier. An optical filter is used to filter out the amplified spontaneous emission (ASE) noise. OFDM demodulation is performed including removing of cyclic prefix (CP^{-1}), S/P conversion, FFT (for OFDM demodulation), post detection OFDM equalization. Then the CI-despreading is performed, which is followed by symbol de-mapping and P/S.

4 Simulation Results

The number of subcarrier used here is $N = 512$. For subcarrier modulation, 4-QAM and 16-QAM are considered. The cyclic prefix, relative to OFDM symbol duration, is $T_{CP}/T = 1/16$, which is enough to compensate for the

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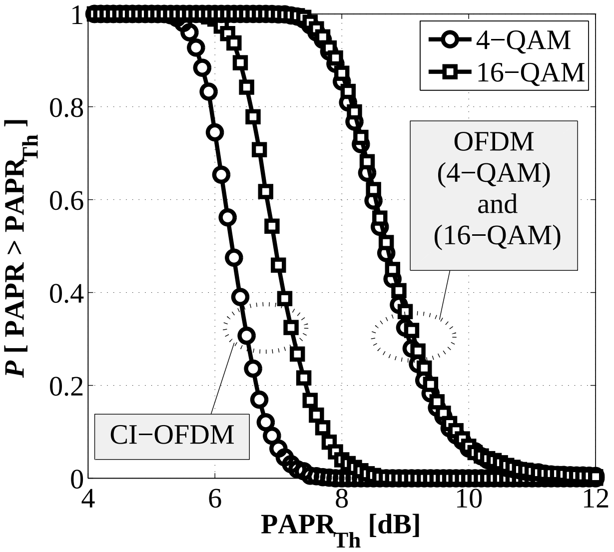

Fig.3 PAPR performance for conventional OFDM and CI-OFDM with 4-QAM (10Gb/s) and 16-QAM (20Gb/s).

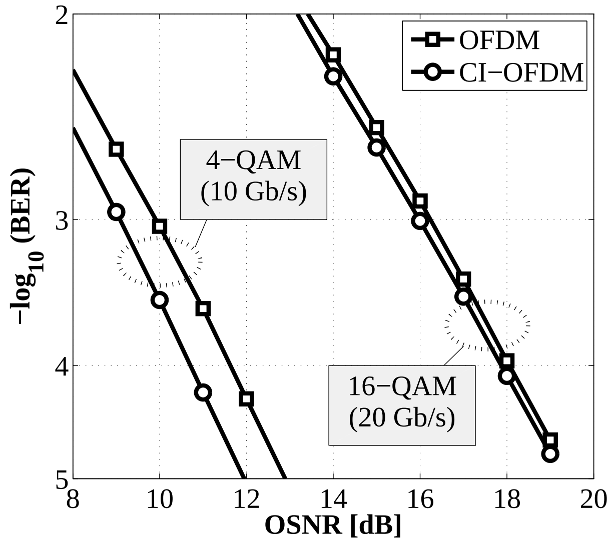

Fig.5 Receiver sensitivity for conventional OFDM and CI-OFDM with 4-QAM (10Gb/s) and 16-QAM (20Gb/s). For both cases, an OMI= σ_x/V_π=0.1.

chromatic dispersion induced inter-symbol interference (ISI). The carrier to SSB power ratio is set to one for optimum receiver sensitivity [8]. A nominal baud rate of 5.6844 GBaud, including the overhead of CP and forward error correction (FEC=7%), was used for both modulation formats. The received raw bit rate, after removing of CP and FEC is 10 Gb/s and 20 Gb/s for 4-QAM and 16-QAM, respectively.

4.1 PAPR Performance

Fig. 3 illustrates the PAPR performance of the two systems for 4-QAM and 16-QAM. It can be seen that conventional OFDM exhibits higher PAPR than CI-OFDM. The PAPRs of both formats are similar in OFDM system, while in CI-OFDM 16-QAM has higher PAPR than 4-QAM. It follows that increasing the modulation level cancels some performance benefits of CI-OFDM.

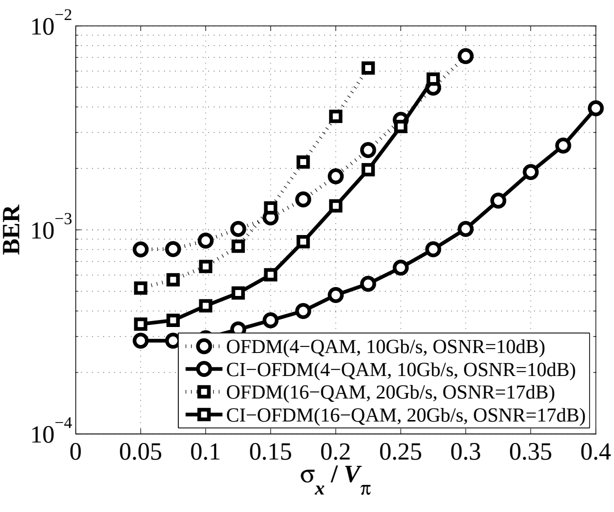

Fig.4 Impact of MZM nonlinearity for conventional OFDM and CI-OFDM with 4-QAM (10Gb/s) and 16-QAM (20Gb/s).

4.2 MZM Nonlinearity

For MZM nonlinearity investigation, variable optical modulation index (OMI= σ_x/V_π) is considered, which is defined as the standard deviation of the OFDM driving signal σ_x divided by the MZM switching voltage V_π. The BER is measured at OSNR=10dB and 17dB for modulation formats of 4-QAM and 16-QAM, respectively. **Fig. 4** shows the results for both cases. In case of 4-QAM (10Gb/s) at BER=10^{-3}, the OMI can be increased from OMI=0.125 for conventional OFDM to OMI=0.3 for CI-OFDM. While, for the case of 16-QAM (20Gb/s) at BER=10^{-3}, the OMI can be increased from OMI=0.125 for conventional OFDM to OMI=0.175 for CI-OFDM. Increasing the OMI is desirable to reduce the gain of the optical amplifier which is required after the MZM to boost the signal into the fiber [9].

4.3 Receiver Sensitivity

For noise performance investigation, a back-to-back (B2B) simulation is carried out for both techniques, namely OFDM and CI-OFDM. An OMI= σ_x/V_π=0.1 is used for both techniques. **Fig. 5** shows the results of the receiver sensitivity with different modulation formats. It can be seen that the noise tolerance decreases as the modulation level increased from 4-QAM to 16-QAM. The OSNR improvements for CI-OFDM system are $\approx$1dB and <0.5dB for 4-QAM and 16-QAM, respectively.

4.4 Fiber Nonlinearity

For nonlinearity comparison, the *Q*-factor is considered as the metric of transmission performance, which is defined

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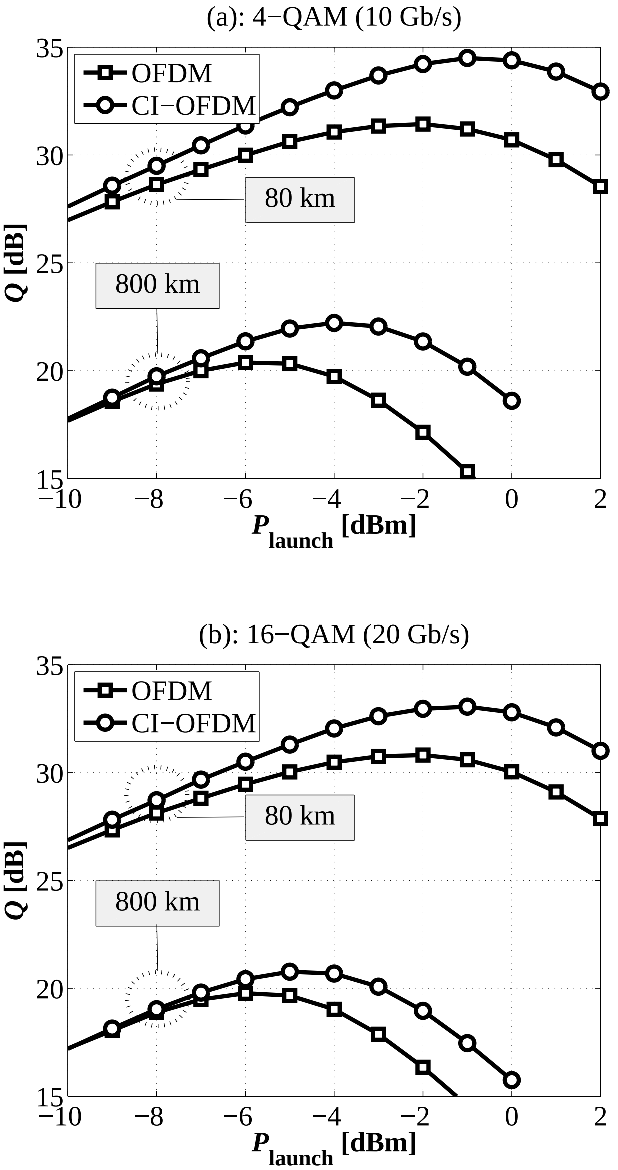

Fig.6 System *Q*-value as a function of fiber launch power for conventional OFDM and CI-OFDM systems in a single channel for 80km and 800km transmission lengths: (a) 4-QAm (10Gb/s) and (b) 16-QAM (20Gb/s).

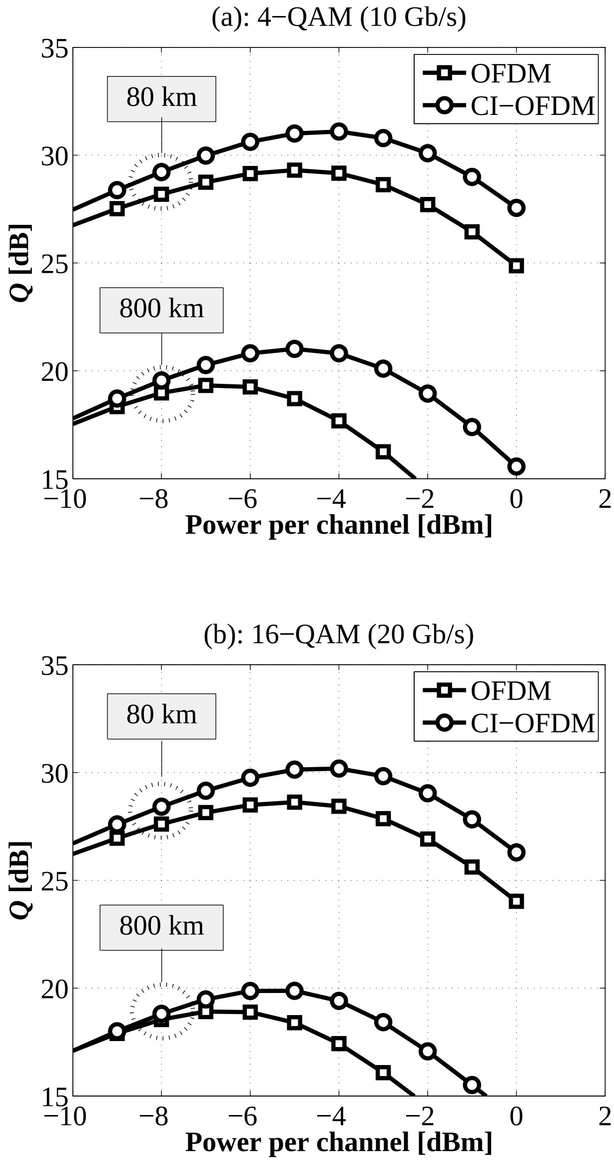

Fig.7 System *Q*-value as a function of fiber launch power for conventional OFDM and CI-OFDM systems in 5-WDM channels for 80km and 800km transmission lengths: (a) 4-QAm (10Gb/s) and (b) 16-QAM (20Gb/s).

as $Q_{\mathrm{dB}} = 20 \cdot \log_{10}(q)$. The *q*-value (which is averaged over all constellation clusters) was calculated as $q^2 = |\mu|^2/\sigma^2$, where $\mu = \mu_{\mathrm{R}} + j\mu_{\mathrm{I}}$ and σ^2 are the mean-value and variance of a particular cluster. **Fig. 6** shows the results for both modulation formats with different fiber lengths. From **Fig. 6(a)** (4-QAM) we can see the improvement in *Q*-factor of CI-OFDM over OFDM which is about ≈ 3dB and ≈ 2dB at optimum input powers for 80 km and 800 km transmissions, respectively. From **Fig. 6(b)** (16-QAM) the improvement in *Q*-factor is about ≈ 2dB and ≈ 1dB at optimum input powers for 80 km and 800 km transmissions, respectively.

The results for 5-WDM channels within 25 GHz grid are shown in **Fig.7**. For WDM transmission, *q*-value is averaged over all channels. At optimum input powers per channel, for 4-QAM in **Fig. 7(a)** we have an improvement in *Q*-factor of ≈ 1.6dB and ≈ 1dB for 80 km and 800 km transmissions, respectively, while for 16-QAM in **Fig. 7(b)** an improvement in *Q*-factor of ≈ 1.2dB and ≈ 0.8dB is achieved for 80 km and 800 km transmissions, respectively.

5 Conclusions

CI-OFDM, as a PAPR reduction technique with high flexibility, has been investigated in direct detection optical systems. Compared to conventional OFDM, using CI-OFDM a PAPR reduction, of ~3dB and ~2dB in 4-QAM

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and 16-QAM has been achieved, respectively. By simulation, the amplitude of the OFDM driving signal can be increased using CI-OFDM. In addition, considerable improvement in nonlinear tolerance has been achieved by using CI-OFDM technique both in a single channel and in 5-WDM channel transmissions.

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