The robustness of subcarrier-index modulation in 16-QAM CO-OFDM system with 1024-point FFT

Omar H. A. Jan,[*] David Sandel, Kidsanapong Puntsri, Ali Al-Bermani, Mohamed El-Darawy, and Reinhold Noé

University of Paderborn, EIM-E, Warburger Str. 100, 33098 Paderborn, Germany
[*]omar@ont.upb.de

Abstract: We present in numerical simulations the robustness of subcarrier index modulation (SIM) OFDM to combat laser phase noise. The ability of using DFB lasers with SIM-OFDM in 16-QAM CO-OFDM system with 1024-point FFT has been verified. Although SIM-OFDM has lower spectral efficiency compared to the conventional CO-OFDM system, it is a good candidate for 16-QAM CO-OFDM system with 1024-point FFT which uses a DFB laser of 1 MHz linewidth. In addition, we show the tolerance of SIM-OFDM for mitigation of fiber nonlinearities in long-haul CO-OFDM system. The simulation results show a significant penalty reduction, essentially that due to SPM.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (060.4370) Nonlinear optics, fibers.

References and links

1. A. J. Lowery and L. B. Du, "Optical orthogonal division multiplexing for long haul optical communications: A review of the first five years," Opt. Fiber Technol. **17**(5), 421–438 (2011).
2. B. Inan, S. Adhikari, O. Karakaya, P. Kainzmaier, M. Mocker, H. von Kirchbauer, N. Hanik, and S. L. Jansen, "Real-time 93.8-Gb/s polarization-multiplexed OFDM transmitter with 1024-point IFFT," Opt. Express **19**(26), B64–B68 (2011).
3. R. Schmogrow, M. Winter, B. Nebendahl, D. Hillerkuss, J. Meyer, M. Dreschmann, M. Huebner, J. Becker, C. Koos, W. Freude, and J. Leuthold, "101.5 Gbit/s Real-Time OFDM Transmitter with 16QAM Modulated Subcarriers," OFC, OWE5 (2011).
4. S. Adhikari, B. Inan, O. Karakaya, W. Rosenkranz, and S. L. Jansen, "FFT optimization for practical OFDM implementations," ECOC, 1–3 (2011).
5. S. L. Jansen, I. Morita, T. C. W. Schenk, N. Takeda, and H. Tanaka, "Coherent Optical 25.8-Gb/s OFDM Transmission over 4,160-km SSMF," J. Lightwave Technol. **26**(1), 6–15 (2008).
6. B. Inan, S. Randel, S. L. Jansen, A. Lobato, S. Adhikari, and N. Hanik, "Pilot-tone-Based Nonlinearity Compensation for Optical OFDM Systems," ECOC, Tu.4.A.6 (2010).
7. Y. Zhao and S. G. Haggman, "Intercarrier interference self-cancellation scheme for OFDM mobile communication systems," IEEE Trans. Commun. **49**(7), 1185–1191 (2001).
8. B. Goebel, S. Hellerbrand, N. Haufe, and N. Hanik, "PAPR reduction techniques for coherent optical OFDM transmission," ICTON, 1–4 (2009).
9. B. S. Krongold, Y. Tang, and W. Shieh, "Fiber nonlinearity mitigation by PAPR reduction in coherent optical OFDM systems via active constellation extension," ECOC, 1–2 (2008).
10. H. Bao and W. Shieh, "Transmission simulation of coherent optical OFDM signals in WDM systems," Opt. Express **15**(8), 4410–4418 (2007).
11. O. Jan, D. Sandel, M. El-Darawy, K. Puntsri, A. Al-Bermani, and R. Noé, "Fiber nonlinearity tolerance of SIM-OFDM in CO-OFDM transmission," OECC, 335–336 (2012).
12. R. Abu-alhiga and H. Haas, "Subcarrier-index modulation OFDM," IEEE Pers. Ind. and Mobile Radio Comm., 177–181 (2009).

1. Introduction

Coherent optical orthogonal frequency-division multiplexing (CO-OFDM) has been proposed as a future candidate for long-haul optical transmission. The ease of chromatic dispersion

#176964 - $15.00 USD Received 1 Oct 2012; revised 8 Nov 2012; accepted 8 Nov 2012; published 13 Dec 2012

(CD) and polarization-mode dispersion (PMD) compensation together with high spectral efficiency are the major advantages of CO-OFDM [1]. However, CO-OFDM suffers from laser phase noise and fiber nonlinearities which strongly degrade system performance. Recently, a 93.8 Gb/s transmission with 4-QAM, 1024-point FFT, 25 GS/s, and polarization-division multiplexing has been demonstrated [2]. A 101.5 Gb/s transmission with 16-QAM, 64-point FFT, 28 GS/s and a single polarization has also been realized [3]. Furthermore, an experiment with 4-QAM, various FFT sizes from 512 to 4096, 25 GS/s and a single polarization has investigated the limitation of using large FFT sizes in the presence of laser phase noise [4]. All experiments above have used external cavity lasers (ECL) with linewidths of ~100 kHz. On the other hand, by considering the same sampling rate, compared to 4-QAM, high-order modulation formats such as 16-QAM suffer more severely from laser phase noise. To our knowledge, none of the experiments reported so far has investigated the usage of DFB lasers with large linewidths for high-order modulation formats and large FFT sizes.

To enable the usage of DFB laser, several techniques have been simulated. One elegant method is the RF pilot (RFP) technique which not only compensates for the effect of laser phase noise but is also able to mitigate fiber nonlinearities [5, 6]. This technique is also used in most reported experiments with ECL lasers. In this paper, we first show a limitation of RFP compensation for large laser linewidths in a 16-QAM, 1024-point FFT, 25 GS/s system. In mobile communication systems, inter-carrier interference (ICI) self-cancellation shows a good mitigation of carrier frequency offsets (CFO) between transmitted and received carrier frequencies [7]. This, in turn, causes a loss of orthogonality between subcarriers which leads to ICI. So, we secondly apply ICI self-cancellation with the RFP for laser phase noise compensation in the CO-OFDM in order to enable the usage of DFB lasers. Even though ICI self-cancellation significantly reduces the impact of laser phase noise the significantly lower bandwidth efficiency of this technique is a major drawback. On the other side and for long-haul transmission, several techniques have been proposed to mitigate the fiber nonlinearities by reducing the peak-to-average power ratio (PAPR) in OFDM [8, 9]. Nevertheless, the PAPR reduction in long-haul transmission system becomes insignificant because the PAPR quickly increases due to fiber dispersion [1]. Partial carrier filling (PCF) [10, 11] is introduced to reduce the effect of SPM, However, PCF degrades also the bandwidth efficiency.

Recently, a new transmission approach, called subcarrier-index modulation (SIM) has been integrated in OFDM systems [12]. This approach shows an improvement compared to conventional OFDM. Then, we propose the SIM-OFDM technique for a CO-OFDM system, which has not yet been studied. The simulation results show a tolerance to laser phase noise when the SIM-OFDM with the RFP is applied, compared to conventional CO-OFDM with the RFP. Moreover, we show the performance of SIM-OFDM technique for long-haul CO-OFDM system, in which the fiber nonlinearities are dominated. The numerical results depict a tolerance towards fiber SPM.

2. Concept of self-cancellation technique

The basic idea of this technique is transmitted an inverted *M*-QAM data on pairs of adjacent subcarriers using $X_i^{(k+1)} = -X_i^{(k)}$ as shown in Fig. 1(a), where k is the index of the even-numbered subcarrier, i is the OFDM symbol and X is the *M*-QAM data symbol.

$$Y''(k) = Y'(k) - Y'(k-1). \tag{1}$$

In Eq. (1), ICI at the receiver is cancelled by subtracting each received odd-numbered data subcarrier $(k+1)$ from the previous data subcarrier (k) in the frequency domain [7].

#176964 - $15.00 USD Received 1 Oct 2012; revised 8 Nov 2012; accepted 8 Nov 2012; published 13 Dec 2012

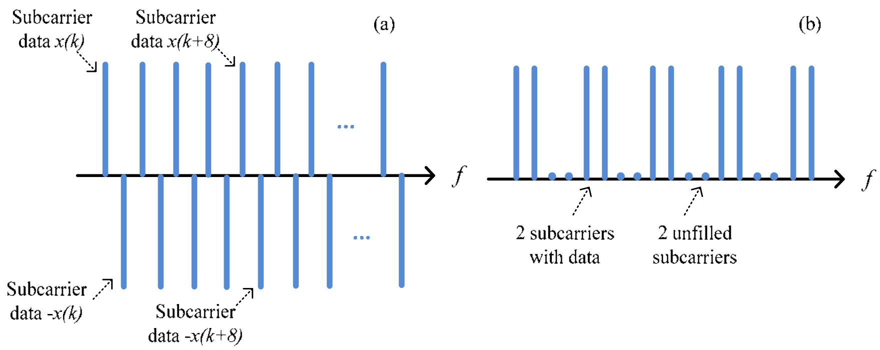

Fig. 1. (a) Scheme of self-cancellation technique, (b) Scheme of PCF technique.

By doing so, the residual ICI contained in the received data after the RFP is reduced as the ICI impacts in channels k and $k + 1$ are strongly correlated. Assuming no additional overhead for simplicity, the spectral efficiency of CO-OFDM with self-cancellation technique can be expressed as

$$S_{self-cancelation}[bits/s/Hz] = \frac{1}{2}\log_2(M). \tag{2}$$

M is the number of modulation states. Hence, the self-cancellation technique has only half the bandwidth efficiency of conventional CO-OFDM system. One possibility to overcome this drawback, the bandwidth of OFDM signal can be increased or a large alphabet size must be used.

3. Partial carrier filling (PCF) technique

This technique is introduced to mitigate the effect of fiber nonlinearity [10] by assigning data to some adjacent subcarriers followed by empty ones (without data). By doing so, a part of the distortion due to SPM becomes located in the empty sub-carriers. The fill factor (*FF*) of PCF is defined as number of filled subcarriers divided by total number of subcarriers [10]. In this paper we assume 50% FF as shown in Fig. 1(b).

Assuming no additional overhead, the spectral efficiency of PCF can be defined by the same way as for self-cancellation technique in Eq. (2). It can be noticed that the spectral efficiency of the PCF technique causes a reduction of bandwidth efficiency by a factor of 2 for the FF of 50% compared to conventional OFDM.

4. Concept of subcarrier-index modulation (SIM-OFDM)

SIM-OFDM exploits the subcarrier index in an on-off keying (OOK) scheme to inform whether symbols are transmitted or not [12]. In the transmitter, before the S/P block, the bit stream is divided into two subsets. The first subset is dedicated to OOK format in which the location of each bit is associated with the index of each subcarrier to activate or deactivate it. The active subcarriers are then modulated by the second subset of the bit stream which is mapped by e. g. 16-QAM while the inactive ones are turned off. Figure 2 shows an example of this technique. The number of bits for the OOK format is equal to the number of subcarriers, after excluding some overhead.

#176964 - $15.00 USD Received 1 Oct 2012; revised 8 Nov 2012; accepted 8 Nov 2012; published 13 Dec 2012

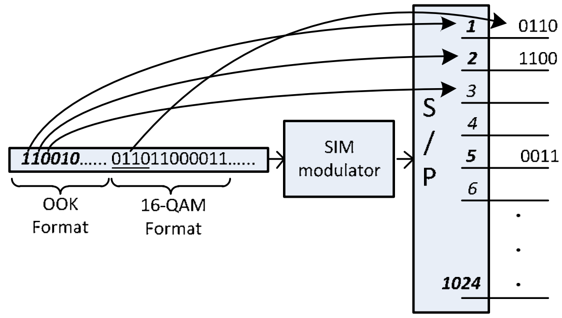

Fig. 2. Subcarrier-index modulation OFDM with 16-QAM and 1024-point FFT.

To do this, an additional block has to be implemented in the transmitter as SIM-OFDM modulator. At the receiver, the first step is to estimate the active and inactive subcarriers in order to demodulate the OOK format, the first subset of bits. The second step is the conventional process of demodulating the active OFDM data. Generally, the SIM-OFDM technique provides zeroed subcarriers in between subcarriers with data. Assuming no additional overhead for simplicity, the spectral efficiency of SIM-OFDM can be expressed as

$$S_{SIM-OFDM}\,[bits\,/\,s\,/\,Hz\,] = 1 + \frac{N_{act}}{N_{FFT}}\log_2(M\,). \tag{3}$$

N_{act} is the number of active subcarriers which depends on the bit probabilities, and N_{FFT} is the FFT size. It is clear that SIM-OFDM shows a higher spectral efficiency by combining OOK format with 16-QAM format compared to both self-cancellation technique and PCF technique.

5. System performance versus phase noise

Figure 3 shows our simulation setup which is based on VPITransmissionMaker. The data are mapped into 16-QAM. A 1024-point FFT with 512 padded zeros is used. 20 subcarriers act as a guard band around the RFP. The cyclic prefix consists of 64 samples. The electrical signal is sampled at 25 GS/s, therefore its bandwidth is ~12 GHz. This baseband OFDM signal is fed to an optical IQ Mach-Zehnder Modulator (IQ-MZM) with extinction ratio of 30dB, where a DC offset generates the pilot tone in the center of the OFDM spectrum. The net bit rate is 45.12 Gb/s for RFP only, 22.56 Gb/s for self-cancellation with the RFP and ~33.8 Gb/s for SIM-OFDM with the RFP. A back-to-back transmission simulation was carried out to evaluate the impact of laser phase noise only. The pilot-to-signal ratio (PSR) of the RFP technique in this simulation is around –2 dB. Four schemes have been simulated: conventional CO-OFDM with the RFP referred to (RFP only), SIM-OFDM with the RFP referred to (SIM + RFP), PCF with the RFP referred to (PCF + RFP) and the self-cancellation technique with the RFP referred to (SC + RFP). A perfect frame synchronization and frequency offset compensation are assumed in this paper.

#176964 - $15.00 USD Received 1 Oct 2012; revised 8 Nov 2012; accepted 8 Nov 2012; published 13 Dec 2012

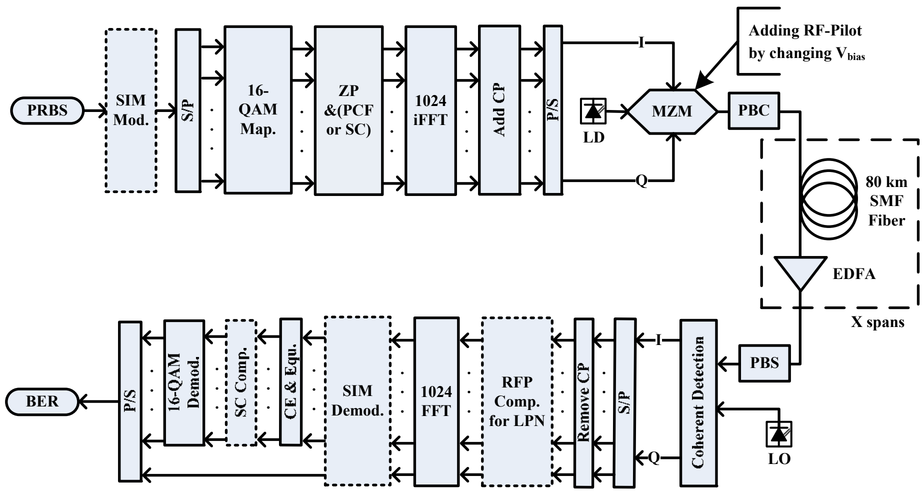

Fig. 3. System setup: (PCF or SC) is not used with No Comp. scheme of nonlinearity effect, biasing MZM to add RFP is not used with all schemes of nonlinearity effect, (PBC, PBS, X spans) blocks are not used with evaluation of laser phase noise, Coherent detection block consists of 90°hybrid and two balance photo-detectors; RFP Comp. block used only with evaluation of laser phase noise.

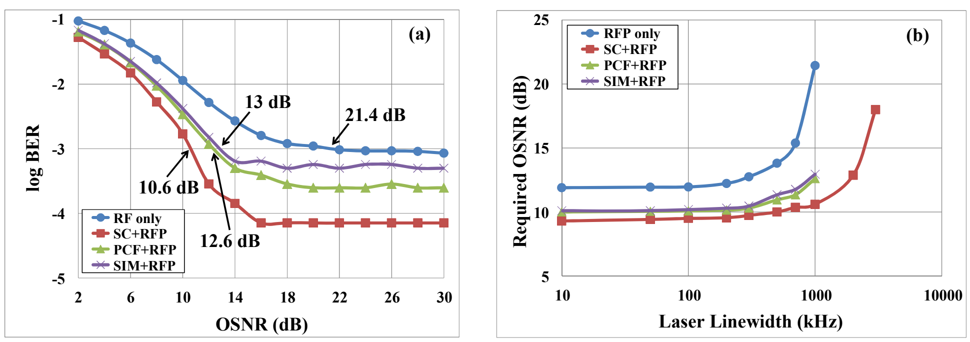

Fig. 4. (a) BER performance for 1 MHz laser linewidth, (b) Required OSNR versus laser linewidth for BER = 10^{-3}.

We have observed that the RFP alone is not very effective for high-order constellations with large FFT size and wide laser lines as shown in Fig. 4(a), where it barely reaches 10^{-3} BER at ~21.4 dB OSNR at 1 MHz laser linewidth. Self-cancellation with the RFP, PCF with the RFP and SIM-OFDM with the RFP can easily give 10^{-3} BER at ~10.6 dB, ~12.6 dB and ~13 dB OSNR at the same linewidth, respectively. The PCF with the RFP is slightly better than SIM-OFDM with the RFP. Figure 4(b) shows the required OSNR for 10^{-3} BER versus various laser line widths. It is clear that both self-cancellation with the RFP and SIM-OFDM with the RFP perform better than RFP only when moving to wider laser lines. Note that the self-cancellation with the RFP can support laser linewidths larger than 1 MHz, but at the cost of bandwidth efficiency. Thus, for 1 MHz laser linewidth, the SIM-OFDM is a good candidate for CO-OFDM system with 16-QAM and 1024 FFT size.

6. System performance versus fiber nonlinearity

In addition to the same simulation parameters of above, the optical transmission link is modeled by spans of 80 km SSMF fiber with erbium doped fiber amplifiers (EDFAs) in between which have a noise figure of 6 dB. A fiber loss of 0.2 dB/km, a chromatic dispersion

#176964 - $15.00 USD Received 1 Oct 2012; revised 8 Nov 2012; accepted 8 Nov 2012; published 13 Dec 2012

of 17 ps nm^{-1} km^{-1}, a polarization mode dispersion of 0.1 ps km$^{-1/2}$ and a nonlinear coefficient (γ) of 1.3 W^{-1} km^{-1} are modeled. Polarization division multiplex (PDM) is used, so that the net bit rate is doubled. The nonlinear response of the MZM has not been considered. Therefore the net bit rate becomes 93.56 Gb/s for no compensation (No Comp.), 46.78 Gb/s for PCF and ~70 Gb/s for SIM-OFDM. It should be noted that the No Comp. refers to neither PCF, nor SIM-OFDM is used and the RFP technique does not employ here. To evaluate the tolerance due to fiber nonlinearity only, the laser is assumed to have no phase noise.

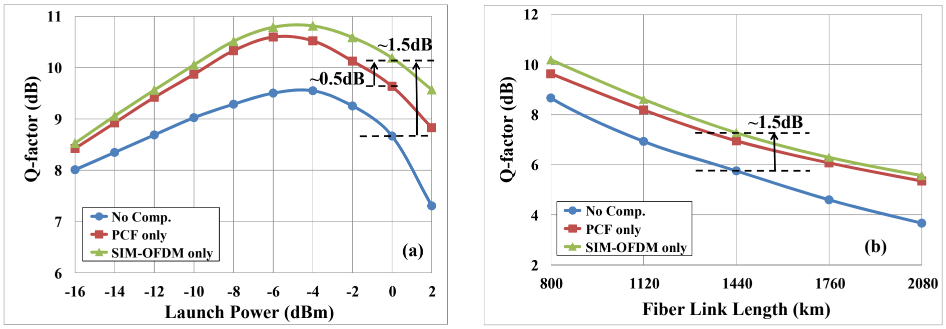

Fig. 5. (a) System Q-factor versus optical launch power over 800 km fiber length, (b) System Q-factor versus fiber length at 0 dBm launch power

As both SIM-OFDM and PCF technique provide wide separation between the subcarriers, we have noticed that the SIM-OFDM is very attractive for high-order constellations with large FFT size and long fiber link compared to the PCF technique. The benefit of using larger FFT size here is to reduce the overhead of cyclic prefix which required avoiding the Inter-symbol Interference (ISI). Figure 5(a) shows the Q-factor versus launch power over 800 km SMF fiber. At 0 dBm launch power when total nonlinearity is high, SIM-OFDM gives ~0.5dB and ~1.5dB improvement in Q-factor compared to No Comp. and PCF technique only respectively. This shows that the SIM-OFDM mitigates the effect of SPM very much. Figure 5(b) shows the system Q-factor versus fiber length at 0 dBm launch power. Over 1440 km, SIM-OFDM gives ~1.5 dB improvement compared to no compensation and slightly better than PCF technique. This shows that SIM-OFDM is significantly reduced SPM penalty of the fiber and therefore SIM-OFDM support long fiber link.

7. Conclusion

In this paper, simulations with laser linewidths of 1 MHz (typical for DFB lasers), 16-QAM modulation format and 1024-point FFT size have been carried out. The net bit rate is 45.12 Gb/s, 22.56 Gb/s and ~33.8 Gb/s for RFP only, self-cancellation with the RFP and SIM-OFDM with the RFP, respectively. The results show that the self-cancellation technique with the RFP is most robust against laser phase noise for 16-QAM CO-OFDM with 1024-point FFT, but its spectral efficiency is the major drawback. SIM-OFDM with the RFP gives also an evidently higher tolerance due to laser phase noise and a better bandwidth efficiency compared to the self-cancellation technique. SIM-OFDM marks the possibility to use DFB lasers of 1 MHz linewidth in 16-QAM systems with 1024-point FFT. In addition, we prove that SIM-OFDM has significant improvement on the Q-factor when fiber nonlinearity is taken into account at high launch power. As dual polarization multiplexing is employed and no guard band for RFP, the net bit rate becomes 93.56 Gb/s, 46.78 Gb/s and ~70 Gb/s for No Comp., PCF and SIM-OFDM, respectively. This gives the possibility to be used for long-haul transmission when the nonlinearities of the fiber are dominated. Another investigation not addressed in this paper is the evaluation of self-cancelation technique performance in present of fiber nonlinearities.

#176964 - $15.00 USD Received 1 Oct 2012; revised 8 Nov 2012; accepted 8 Nov 2012; published 13 Dec 2012