Performance Analysis of Optical OFDM Systems

S. Hussin, K. Puntsri, and R. Noé
Optical Communication and High Frequency Engineering Department
University Of Paderborn
Paderborn, Germany
{hussin, puntsri}@ont.upb.de, noe@upb.de

Abstract—Orthogonal Frequency Division Multiplexing (OFDM) has been proposed as a promising technology for high speed optical communication [1]. In this paper, we provide a performance analysis of direct detection optical OFDM (DDO-OFDM), coherent optical OFDM (CO-OFDM) and self coherent optical (SCO-OFDM). We first review the theoretical fundamentals for Optical OFDM and the differences between the three systems. Then, phase noise (PN) effects for various laser linewidths and the effect of the received optical power (ROP) on the system performance for these optical OFDM systems are compared. In this article, we provide the first comparative analysis between the three existing optical OFDM systems. This analysis is simulated using VPItransmissionMaker™ V8.5. Finally, the best optical OFDM system with high performance is shown as a future trend.

Keywords— optical OFDM, direct detection, coherent detection, self coherent detection

I. INTRODUCTION

OFDM is a modulation technology which is used in many broadband wired and wireless communication systems to combat the multipath fading. The application of OFDM in optical communication systems has been investigated recently. The optical OFDM systems can be classified into three approaches according to the detection scheme. These approaches are: (I) DDO-OFDM was first investigated in 2006 by Lowery [2]. (II) CO-OFDM, which can mitigate the chromatic dispersion (CD), was also investigated in 2006 by Shieh [3]. In 2007, Shieh proved that CO-OFDM can mitigate polarization mode dispersion (PMD) [4]. (III) SCO-OFDM was investigated in 2008 by Xu [5]. This scheme modifies CO-OFDM in so far as it extracts the optical carrier from the received optical OFDM signal at the receiver for coherent interferene. Recently, an increasing number of papers on the simulation and experimental analysis for high data rate optical OFDM have been published. For DDO-OFDM, simulation results of 10 Gbps over 4000 km transmission standard single mode fiber (SSMF) were presented in [2], while experimental results of 24 Gbps over 800 km transmission SSMF were reported in [6]. For CO-OFDM, the transmission of 10 Gbps over 3000 km SSMF was simulated in [3], experimental results of 8 Gbps transmission over 1000 km SSMF are reported in [7], the transmission of 25.8 Gbps over 4160 km SSMF was demonstrated in [8], and simulation results of 100 Gbps back-to-back transmission are reported in [9]. For SCO-OFDM, simulation results of 10 Gbps back-to-back transmission are reported in [5], while demonstration results of 15.3Gbps over 81.4 km transmissions are presented in [10].

There are salient differences between DDO-OFDM and CO-OFDM as follows: DDO-OFDM is more suitable for short distance and inexpensive applications as it requires fewer components at the transmitter and receiver than CO-OFDM, while it needs a guard band between the optical carrier and the OFDM band, to avoid inter-modulations in the photodiode [2]. Therefore, it increases the bandwidth requirements and decreases the spectral efficiency. Moreover, it measures only the amplitude of the optical signal. CO-OFDM is suitable for long haul transmission with high-bit-rate. To achieve high performance for CO-OFDM, it requires a transmitter laser and a local oscillator (LO) laser with a particularly narrow linewidth (Δν) and effective digital signal processing (DSP). The receiver involves extra signal processing for phase and frequency estimation to compensate the phase noise and the frequency offset between transmitter laser and LO. Polarization diversity detection increases the complexity of the DSP at the receiver part. Therefore, it will be more expensive than DDO-OFDM. Moreover, it allows detecting phase, frequency and the amplitude of the transmitted signal. SCO-OFDM extracts the optical carrier from the received optical OFDM signal with a band-pass filter (BPF), so it looks like homodyne detection. Since the two interfering optical signals come from the same laser source, their polarization and phase noise are identical. Therefore the complexity of DSP is decreased. Furthermore no LO is required at the receiver.

Is this paper, we elaborate and compare the performance of these three existing optical OFDM systems in more detail. Results of a simulated 20 Gbps in back-to-back transmission are reported. The paper is organized as follows: In section II, the optical OFDM systems with the different aspects are described in detail. Section III provides the simulation setup. In section IV, we present and discuss the results and compare them. Finally, we present our conclusions in section V.

II. ARCHITECTURE DESIGN

This section represents the design concepts used in the three systems with the main differences between them. Fig. 1 shows the block diagram of three existing optical OFDM back-to-back transmission, including four main blocks [2], [5], [11]: RF-OFDM-transmitter (Tx), RF-to-optical (RTO) up-converter, optical-to-RF (OTR) down-converter and RF-OFDM-receiver (Rx). The RF-OFDM-Tx and RF-OFDM-Rx are common parts between three existing systems while the
RTO up-converter and OTR down-converter blocks differ. A very important assumption for OFDM is the linearity in modulation and demodulation [12]. A linear RTO up-converter and linear OTR down-converter can be obtained in principle by biasing Mach Zehnder modulator (MZM) at quadrature or null point in order to obtain a linear transformation between RF signal and optical signal [3], [11], [13]. Fig. 1 shows the details of the considered system setups. In the next section we will expand the setups.

1. RF-OFDM-Tx

The input high-bit-rate ($R_s$) serial data are converted to low-bit-rate ($R_s/N$) parallel blocks of bits where $N$ is the number of parallel data paths. These blocks of bits contain information symbols of $N_{sc}$ “subcarriers”. The information symbols are mapped by quadrature amplitude modulation (QAM) onto $N_{sc}$ orthogonal carriers with equally spaced frequencies. To avoid aliasing due to the sampling process of the digital-to-analog converter (DAC), zero padding (ZP) is needed. This shifts the aliases away from the OFDM signal. By inverse fast Fourier transformation (IFFT), one obtains the time-domain OFDM signal. The IFFT size determines the numbers of subcarriers and the numbers of ZP. The ZP may be inserted in the middle of the IFFT sequence or at its edges. Usually half of the input IFFT sequence is used for ZP while the other half is used for subcarriers because of the required Hermitian symmetry. The IFFT size usually lies between 128 [7] and 1024 [2]. Increasing the IFFT size makes the signal less susceptible to intersymbol interference (ISI) between OFDM symbols. Its drawbacks are the increased processing complexity at transmitter and receiver and the increased sensitivity to laser phase noise in case of coherent detection.

Each OFDM symbol has a duration $T_s = N_{sc} / R_s$ which is $N_{sc}$ times longer than in a single carrier system. This reduces the chromatic dispersion relative to the symbol time. To avoid ISI between OFDM symbols, a guard time, called cyclic prefix (CP), is inserted for each OFDM symbol after the IFFT. The CP is formed by copying the last $N_g$ samples of each OFDM symbol to the beginning of the same symbol. The CP produces overhead due to it contains redundant information. To minimize the overhead, a good selection of minimum guard time $T_g$, represented in samples $N_g$, can be written as [8]

$$N_g = T_g \times f_s$$  \hspace{1cm} (1)

where $f_s$ is the sampling frequency of the DAC used to generate the OFDM signal. The CP overhead is [8]

$$\varepsilon_{cp} = \frac{N_g}{N_{sc}}$$  \hspace{1cm} (2)

Note that a large IFFT size reduces the CP overhead ($\varepsilon_{cp}$). Suitable values for $\varepsilon_{cp}$ are 0.125 [3] and 0.0625 [5], [6], [10]. Finally, the information symbols at the output of IFFT are serialized and converted to analog electrical signal, using a DAC. This block is common for the three optical OFDM systems.

2. RTO up-converter

In order to transform the RF signal linearly to an optical signal two different configurations can be applied in the Tx as shown in Fig. 1 [11].

- Intermediate frequency (IF) conversion architecture
  The OFDM baseband signal is up-converted to an IF in the electrical domain, and then the new RF-OFDM signal is up-converted to the optical domain using one MZM. The optical OFDM signal has double side bands (DSB). Due to the symmetry of the optical OFDM spectra at both sides of the optical carrier, one must suppress one of the side-bands and optical carrier by an optical band-pass filter (OBPF), to get the desired spectral efficiency; see inset (B) of Fig. 1. The efficiency of this architecture depends on the performance of the OBPF being used. It is more suitable for DDO-OFDM [2].

- Direct up-conversion architecture
  It uses an optical IQ-MZM which consists of two null biased MZMs with a 90° phase difference between them band as shown in inset (A) of Fig. 1. The I/Q components of the baseband OFDM signal are up
converted directly to only one optical signal. There is no DSB problem, nor is an OBPF required. The need for precise adjustment of three bias voltages is the main disadvantage of this architecture. It is more suitable for CO-OFDM and SCO-OFDM systems [3], [5].

3. OTR down-converter

The receiver must linearly convert the optical signal to an RF signal, which reverses the previous operation. Two different configurations can also be applied as shown in Fig. 1:

- Intermediate frequency (IF) conversion architecture
  After transmission of the optical OFDM signal through the fiber link the photodiode (PD) down-converts the optical signal to an electrical IF signal. After splitting the I/Q components of RF-OFDM signal the RF-OFDM baseband signal is obtained, by mixing with 0° and 90° phases of the LO at the IF as shown in inset (B) of Fig. 1. This architecture is always preferred for DDO-OFDM systems [2]. By replacing the PD and the splitter by the OTR down-converter block of inset (A) of Fig. 1, we obtain another architecture that can be used for CO-OFDM systems [11].

- Direct down-conversion architecture
  The optical OFDM signal is down-converted using an optical 90° hybrid and two pairs of balanced detectors to obtain the I/Q components of RF baseband OFDM signal as shown in inset (A) of Fig. 1. This architecture is normally used in CO-OFDM systems [11]. By replacing inset (C) by inset (D), one can obtain a SCO-OFDM system [5]. The received optical OFDM signal is split into two portions by an optical 3-dB (or similar) coupler. One flows directly to an optical 90° hybrid and the other is passed through an OBPF which extracts the optical carrier. Since the extracted optical carrier and the optical OFDM signal come from the same single source, one can avoid the need of polarization diversity detection. However, polarization mode dispersion (PMD) must be sufficiently low, and a factor of two is lost in spectral efficiency compared to polarization-multiplexed systems.

4. RF-OFDM-Rx

The I/Q components of RF-OFDM signal are digitized in ADCs. Phase noise of transmitter laser and LO need to be compensated. The digital serial signal is converted to complex parallel data blocks using an S/P converter, and the CP is removed. By FFT the OFDM signal is converted back to the frequency domain. After removal of ZP each QAM symbol is demodulated by QAM de-mapping. This produces parallel data. This data can be converted to serial data by P/S conversion. This block is also common for three optical OFDM systems.

From the blocks explained until now we always use RF-OFDM-Tx and RF-OFDM-Rx blocks as a common parts while we change the RTO up/down-conversion blocks. So, we can produce a DDO-OFDM system by using inset (B) of Fig. 1 together with the common parts, or a CO-OFDM by using inset (A) instead of inset (B). An SCO-OFDM system can be obtained by using inset (D) instead of inset (C).

III. SIMULATION SETUP

The generation and analysis of the OFDM signal and systems performance are simulated, using VPItransmissionMaker™ V8.5. An OFDM signal with a data rate of 20 Gb/s is generated from a pseudorandom binary sequence (PRBS) of length 2^13-1. This bit stream was converted from serial to parallel, then mapped with 4-QAM (QPSK). An IF/FFT size of 1024 is used with 512 OFDM subcarriers and 512 ZP at the edges of the FFT. A CP having 12.5% of the symbol length is added. A laser with 1 MHz linewidth is used to generate a continuous signal at 193.1 THz. This is modulated with the OFDM signal in a null-biased IQ-MZM for CO-OFDM or SCO-OFDM systems. In contrast, for the DDO-OFDM system we use an IF of 12 GHz that is up-converted into an optical OFDM signal band above the optical carrier as shown in Fig. 2. This increases the bandwidth of the channel and decreases the spectrum efficiency. This guard band avoids intermodulation distortions in the photodiode. A MZM up-convert the RF OFDM signal to the optical domain.

![Optical Spectrum](image)

Fig. 2: Optical OFDM spectrum at Tx for DDO-OFDM

This guard band is not needed in CO-OFDM or SCO-OFDM systems (Fig. 3) because both sidebands are homodyne (for SCO-OFDM) or heterodyne (for CO-OFDM) into the baseband, where I and Q components are available.

![Optical Spectrum](image)

Fig. 3: Optical OFDM spectrum at Tx for CO-OFDM and SCO-OFDM

To test the optical signal to noise ratio (OSNR) performance, noise is added to control the received OSNR. The main drawback of the coherent reception is the tough requirement on Δν. We assume equal Δν for transmitter and LO lasers.

In [5], the authors compared SCO-OFDM with CO-OFDM and investigated the performance. CO-OFDM was better than SCO-OFDM. They mentioned also the bandwidth of the BPF...
which extracts the optical carrier at the receiver. The quality of the extracted optical carrier is reduced by amplified spontaneous emission (ASE), and the larger the filter bandwidth, the more noise passes with the optical carrier. Therefore a narrow bandwidth filter will improve the performance of SCO-OFDM. But the authors did not provide any result about a low-bandwidth filter. In this paper, we give the performance of SCO-OFDM with different filter bandwidths and compare this to CO-OFDM.

Fig. 5 presents the back-to-back bit error ratio (BER) performance as a function of OSNR. The OBPF bandwidth is varied from 2 to 4 GHz. The required OSNR for a BER $10^{-3}$ is 22.5 dB and 26.1 dB for SCO-OFDM with 2 GHz OBPF width and CO-OFDM, respectively. SCO-OFDM therefore improves the OSNR by 3.6 dB. At an increased bandwidth of 3 GHz, the required OSNR for a BER $10^{-3}$ is 24.6 dB for SCO-OFDM. So the OSNR improvement is decreased to 1.5 dB. For 4 GHz bandwidth, a BER of less than $10^{-3}$ can not be obtained. Performance of SCO-OFDM is obviously improved by reduced the OBPF width.

We can achieve the performance of SCO-OFDM at 2 GHz bandwidth by a modified system design with a narrow optical band-stop filter (OBSF) as shown in Fig. 4. It removes the optical carrier from the optical OFDM signal before the optical 90° hybrid. So the effect of weak optical carrier will be reduced. Compared with SCO-OFDM at 4 GHz bandwidth of OBPF, the required OSNR for a BER $10^{-3}$ is 22.6 dB for the modified (M) SCO-OFDM. Therefore, the MSCO-OFDM can achieve no OSNR improvement and is useless. Moreover, the second filter increases the system complexity and cost. Thus, a narrow OBPF suffices to improve the performance of SCO-OFDM.

An additional 3.6 dB OSNR benefit can be achieved with a SCO-OFDM system which means 10.9 dB OSNR improvement compared with DDO-OFDM. The performance of SCO-OFDM overcomes the performance of CO-OFDM and DDO-OFDM. However, note that with narrow-linewidth lasers, CO-OFDM wouldn’t be worse than SCO-OFDM. Also, CO-OFDM is much less affected by PMD, and allows polarization multiplexing.

**IV. SIMULATION RESULTS AND DISCUSSION**

In Fig. 6, the influence of OSNR on the BER is shown in back-to-back configuration. The BER is simulated for $\Delta \nu = 1$MHz and 2 GHz bandwidth of OBPF for SCO-OFDM and ROP = 0 dBm. The required OSNR for BER of $10^{-3}$ is 22.5 dB, 26.1 dB and 33.4 dB for SCO-OFDM, CO-OFDM and DDO-OFDM respectively. Compared with DDO-OFDM, CO-OFDM can improve OSNR by 7.3 dB.

Fig. 7 shows the BER performance of varying $\Delta \nu$ at 0 dBm ROP and 35 dB OSNR. At $\Delta \nu$ of 1 MHz, the BER is $3.85 \times 10^{-3}$, $2.59 \times 10^{-6}$ and $7.22 \times 10^{-7}$ for DDO-OFDM, CO-OFDM and SCO-OFDM respectively. Increased $\Delta \nu$ brings CO-OFDM performance close to that of DDO-OFDM, while SCO-OFDM is not as much affected and performs better than these two, even at 10 MHz linewidth.
Finally, Fig. 8 shows the effect of varying ROP at 35 dB OSNR and 1 MHz linewidth for DDO-OFDM, CO-OFDM and SCO-OFDM back-to-back transmission. The ROP is varied from -40 dBm to 10 dBm. From the simulation results, a BER $10^{-3}$ can be achieved at a ROP of -26.1 dBm and -26 dBm for SCO-OFDM and CO-OFDM, respectively. The ROP difference is about 0.1 dBm. While the BER performance for DDO-OFDM indicates that 35 dB OSNR is not sufficient to transmit with a BER $10^{-3}$, increased ROP does improve the BER as shown in Fig. 8.

V. CONCLUSION

In this paper, we have analyzed the performance of three exiting optical OFDM systems: DDO-OFDM, CO-OFDM and SCO-OFDM. In particular the effect of a narrow OBPF in SCO-OFDM transmission was investigated. Compared to CO-OFDM at 20 Gbps, about 3.6 dB OSNR improvement can be achieved, and 10.9 dB compared with DDO-OFDM. The simulation results show that SCO-OFDM has a good tolerance to laser linewidth.

REFERENCES