Study of Nonlinearity in CO-OFDM for Single Channel and WDM System

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Abstract
In this paper an attempt is made to study the theoretical fundamentals for Coherent optical orthogonal frequency division multiplexing (CO-OFDM) for high speed, long haul optical transmission and investigated the nonlinear effect of a 16-QAM CO-OFDM and WDM CO-OFDM at 10Gbps data rate. We then demonstrated the transmission performance through simulation for single channel CO-OFDM and multi-channel WDM CO-OFDM system with 100GHz channel spacing. The simulation results reveal that single channel CO-OFDM has better transmission performance up to 500km of SSMF without dispersion compensation in comparison to WDM CO-OFDM system where the transmission distance reduced to 400km instead of 500km.

Keywords – OFDM, QAM, nonlinear distortion, nonlinear system, SSMF.

1. Introduction
Orthogonal frequency division multiplexing (OFDM) is an attractive modulation format that recently received a lot of attention in the fiber-optic community [1]. Orthogonal frequency division multiplexing (OFDM) is a multicarrier transmission technique where a data stream is carried with many lower-rate subcarrier tones. In optical communication systems, OFDM has received increased attention as a means to overcome various limitations of optical transmission systems such as modal dispersion, relative intensity noise, chromatic dispersion, polarization mode dispersion and self-phase modulation. Coherent Optical OFDM (CO-OFDM) combines the advantages of ‘coherent detection’ and ‘OFDM modulation’ and possesses many merits that are critical for future high-speed fiber transmission systems.

In this paper some of the basics of an optical OFDM system are discussed. Furthermore, nonlinearity effect on transmission distance is investigated at 10Gbps data rate and the results are presented in the form of simulations.

2. Theoretical fundamentals for OFDM
In this study, we use the OFDM technique to modulate the electrical signal. In a multi-carrier modulation system (MCM), the data stream is parsed into several parallel sub-streams and each sub-stream modulates one subcarrier. A MCM signal at transmitter

\[ s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N} c_{ki} s_k(t-iT_s) \]  

\[ s_k(t) = \prod(t) e^{2\pi j f_k t} \]  

\[ \prod(t) = \begin{cases} 1, & 0 < t \leq T_s \\ 0, & otherwise \end{cases} \]  

\[ s_m = \sum_{k=1}^{N} c_k e^{j2\pi f_k(m-1)/T_s/N} \]  

In an OFDM system, different subcarrier carrier frequencies are chosen so that each subcarrier is
orthogonal to each other. Because of the orthogonality of the OFDM subcarrier, we will have

\[ f_k = \frac{(k-1)}{T_s} \]  

(1.5)

Substituting Eq. 1.5 into Eq.1.4, we get Eq.1.6:

\[ s_m = \sum_{k=1}^{N} c_k e^{j2\pi f_k (m-1)(k-1)/N} \]  

(1.6)

We can see \( s_k \) is the inverse Fourier transforms of input signal \{ \( c_k \) \}. The recovered \{ \( \hat{c}_k \) \} signals would be the Fourier transforms of the received signal \{ \( \hat{s}_k \) \}.

\[ \hat{c}_k = \frac{1}{\sqrt{N}} \sum_{m=1}^{N} \hat{s}_m e^{-j2\pi f_k (m-1)(k-1)/N} \]  

(1.7)

By evaluating Eq.1.6, it is obvious that OFDM signal is a summation of several subcarriers. As a result, OFDM signal would have a higher peak to average power ratio than single carrier signals.

\[ PAPR=\max_{\tau}\frac{\left|s(t)\right|^2}{E\left|\{s(t)\}^2\right|}, \quad \tau \in [0,T_s] \]  

(1.8)

Since OFDM is a multi-carrier system, when passing through a dispersive channel, different subcarrier will transmit at different group velocities, causing dispersions.

3. System description and modeling

In our study, the CO-OFDM system is simulated by a commercial fiber optics system simulation tool, OptiSystem™. It has been used by many researchers to simulate the fiber nonlinearity and dispersion effects in optical communication systems [3], [4]. Our simulation setting takes most key optical communication system/component parameters into account including fiber nonlinearity, noise, dispersion, and PMD, etc. For the sake of simplicity, some effects such as the laser frequency drifting, and filter bandwidth drifting are ignored. The CO-OFDM simulation configuration is illustrated in Fig 1.

![Fig.1: Block diagram of CO-OFDM system.](image)

The data transmission bit rate is 10 Gbps. On the transmitter side, a bit stream is generated using a pseudo random binary sequence generator, and the data is mapped by a 16-QAM encoder. The information stream is further parsed into 512 low speed parallel data subcarriers and processed by the IFFT processor. Cyclic prefix is added to ensure a correct data recovery. The 25 Gbaud rate OFDM in-phase and quadrature parts then pass the low pass filter. The Mach–Zehnder modulator is used to convert electrical signals to optical signals. The laser line width is set at 0.15 MHz, with adjustable launch power. The frequency of the carrier wave is set at 193.1 THz. The optical channel consists of 10 spans of 50 km standard single mode fiber (SSMF), with attenuation = 0.2 dB/km, dispersion = 16 ps/nm/km and nonlinearity coefficient=2.09 /w/km. Fiber dispersion is fully compensated by the dispersion compensation fiber (DCF) in each span which has 0.6 dB/km attenuation, -80 ps/nm/km dispersion and 6.4 w/km nonlinearity coefficient. Both the SSMF and DCF span loss is balanced by a 4 dB noise figure optical amplifier in each loop. Optical Signal to Noise Ratio (OSNR) is measured at the end of transmission to evaluate the system performance. Amplified spontaneous emission (ASE) noise is reduced by an optical filter at the receiver. The local oscillator (LO) laser is assumed to be perfectly aligned with power set at -2dBm and line width equals to 0.15 MHz. The I/Q components of the OFDM signal is recovered by a 12 × 4 90 degree optical hybrid and two pairs of photo-detectors. Photo-detector noise, such as thermal, shot noise, dark
current and ASE noise are included in the simulation. The converted OFDM RF signal is demodulated using FFT processor and the guarding interval is removed. The obtained signals are fed into a 16-QAM decoder. Transmission bits are collected and bit error ratio (BER) is calculated and compared at the end of the receiver.

The resulting electrical signal of I/Q channel after OFDM modulator is visualize by RF spectrum analyzer

![Block diagram for WDM system.](image)

**Fig. 2: Block diagram for WDM system.**

In a WDM setting, 4 channels of 25 Gbaud 16-QAM OFDM signals are transmitted. The carrier wave frequencies are set from 192.9 THz to 193.3 THz, with 100 GHz channel spacing. The transmission length is reduced to 400 km.

4. RESULTS AND DISCUSSIONS

The transmission bit rate is 10Gbps. On the transmitter side, the bit stream is generated using a pseudo random binary sequence generator, and the data is mapped by a 16-QAM encoder. The 16-QAM encoders with Gray coding has three different amplitude levels, as shown in Fig. 3 16-QAM encoders with Gray coding.

![Input signal constellation of 16-QAM encoders.](image)

**Fig. 3: Input signal constellation of 16-QAM encoders.**

![RF OFDM spectrum at transmitter.](image)

**Fig. 4: RF OFDM spectrum at transmitter.**

![RF OFDM spectrum at receiver.](image)

**Fig. 5: RF OFDM spectrum at receiver.**

![Optical OFDM spectrum before optical fiber transmission.](image)

**Fig. 6: Optical OFDM spectrum before optical fiber transmission.**

![Result of optical spectrum analyzer after a pair of Mach-Zehnder modulators](image)
One major drawback about the CO-OFDM system is its vulnerability to fiber nonlinear effects such as self-phase modulation (SPM) and cross-phase modulation (XPM). Both SPM and XPM are caused by the optical signal intensity fluctuation [5]. Since the OFDM system has a high peak-to-average power ratio (PAPR) [5], a CO-OFDM system has more severe SPM and XPM compared with traditional optical communication systems. Because the OFDM is a multi-carrier modulation scheme, the four-wave mixing (FWM) among subcarriers within one channel introduces additional distortion [6]. Due to these nonlinearity optical signal to noise ratio (OSNR) is measured at the end of the transmission channel.

In the WDM system, 4 channels of 10Gbps 16-QAM OFDM signals are transmitted, with 100GHz channel spacing. In each channel, the modulation parameter has the same settings as the single channel system. The four optical carrier frequencies are set at 192.9THz, 193.0THz, 193.1THz, and 193.2THz respectively. The bit stream for each channel is different. The transmission length is reduced to 400km. The signal spectrum of the four-channel WDM CO-OFDM system at the transmitter is shown in Fig. 7.

To evaluate the nonlinear effect of the optical fiber, the signal constellation after transmission, with different fiber length.

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Fig. 7: Optical OFDM spectrum after optical fiber transmission.

Fig. 8: Four channel WDM CO-OFDM signal at the transmitter.

Fig. 9: Output signal constellation of 16 QAM single Channel CO-OFDM systems after different transmission length. A) 100km, B) 200km, C) 400km, D) 500km.
Fig.10: Output signal constellation of 16 QAM WDM CO-OFDM systems after different transmission length. A) 100km, B) 200km, C) 400km, D) 500km.

The constellation of 16-QAM at receiver side for both single CO-OFDM and WDM CO-OFDM is presented. This result show that the distance between two symbols goes closer as transmission distance increases due to nonlinearity in the optical channel.

5. CONCLUSION

In this paper, some important aspects of CO-OFDM fiber optic transmission systems have been discussed and investigations on system nonlinearity of single channel and WDM 16 QAM CO-OFDM at 10Gbps data rate without any dispersion compensation are done. The investigations reveal that single channel CO-OFDM has better performance in terms of transmission distance without dispersion compensation as compared to WDM CO-OFDM system.

6. REFERENCES
