Simulative Investigation of Coherent Optical OFDM Communication with Gbits/s Data Rates

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Abstract--- CO-OFDM has the advantages of both 'coherent detection' and 'OFDM modulation' and provides many merits for future high-speed fiber transmission systems. In this paper, we analyze the performance of Coherent Optical OFDM (CO-OFDM) for different data rates like 1Gbps, 20Gbps and 100Gbps. 4 QAM-OFDM is generated, modulated using MZM and transmitted through the fiber for a distance of 250km. Due to the different nonlinearities of fiber the signal is distorted. At the receiver end the filtered optical signal is converted to electrical signal and OFDM is demodulated. Results shows that at the receiver as the data rate increases, the distortions in the OFDM spectrum and QAM constellations also increase.

Keywords--- OFDM- Orthogonal Frequency Division Multiplexing, Gbps-Giga Bits per Second, MZM- Mach-Zehnder Modulator, QAM- Quadrature Amplitude Modulation

I. INTRODUCTION

ORTHOGONAL frequency division multiplexing (OFDM) is used in different digital standards for broad-range of applications like digital broadcasting and wire-line and wireless communication systems [1]. OFDM can be applied in optical long haul transmission systems and has many advantages over single-carrier modulation format [2]-[4]. Many advantages of the OFDM technique have been demonstrated in the communication sector. Mainly, the frequency spectra of OFDM subcarriers are partially overlapped, resulting in high spectral efficiency. Secondly, the channel dispersion of the transmission system can be easily estimated and removed, and thirdly the signal processing in the OFDM transceiver can utilize the advantage of the efficiency of the FFT/IFFT algorithm which has low computation complexity. Coherent optical OFDM (CO-OFDM) has been proposed as an equivalent optical-domain multi-carrier format for long haul transmission [2]. Incoherent Optical OFDM (IO-OFDM) has also been proposed with similar dispersion tolerance and much simpler detection scheme [3].

But, the CO-OFDM is superior to IO-OFDM in spectral efficiency, OSNR requirement, and Polarization Mode Dispersion insensitivity. OFDM is generally susceptible to nonlinearity and phase noise because of its high peak to average power ratio (PAPR) [1]. Therefore it is very important

to investigate and improve the CO-OFDM system transmission performance including fiber nonlinearity and receiver nonlinearity, in order to ascertain its suitability for optical transmission.

Optical OFDM (O-OFDM) systems provide an accurate solution for 100 Gb/s Ethernet data traffic [5]–[8]. Latest results show the transmission of Tbit/s data rates over a fiber length of 600 km [9]. But the long-haul optical systems are affected by fiber nonlinearity if the optical powers are kept low [10]. This affects the design of long-haul systems; low launch powers reduces the optical signal-to-noise ratio (OSNR) of the given link, thereby limiting the size of the constellation that can be used [11]. Therefore, it is essential to reduce fiber nonlinearity for achieving higher spectral efficiencies in long-haul transmission [11], [12].

CO-OFDM uses different subcarriers in parallel data streams. The M-ary Quadrature Amplitude Modulation (QAM) or Phase Shift Keying (PSK) is used to modulate the subcarriers before modulating with a high frequency microwave carrier. The multicarrier modulation provides strong vigorousness to intersymbol interferences because the duration of symbol is extremely longer than the root-mean-square (RMS) delay of the optical wireless channel. Therefore, O-OFDM multilevel quadrature amplitude modulation (M-QAM) encourages very high data rates [13]–[15]. In the optical communication system, the data is optically modulated and it should be unipolar [15].

High spectral efficiency modulation formats are used for the increasing demand of the channel capacity in optical communications [16]. O-OFDM has been proved to be suitable for 100 plus Gbps systems and CO-OFDM is considered as a emerging technology in future long-haul optical communication networks because of high spectral efficiencies, resistance to polarization dispersion, adjustable bandwidth scalability and allocation [17]. But, an important drawback of the OFDM system is its susceptibility to fiber nonlinearity due to its high peak-to-average power ratio (PAPR) [18].

II. THEORETICAL FUNDAMENTALS FOR CO-OFDM

A. Principle of Orthogonal Frequency-Division Multiplexing (OFDM)

OFDM is a special form of multi-carrier modulation (MCM), an implementation of which is depicted in Fig. 1. The structure of a complex IQ modulator/demodulator, which is normally used in MCM systems, is also shown in the figure. The MCM transmitted signal ' $S(t)$ ' is represented as

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$$S(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{sc}} C_{ki} S_k(t - iT_s) \quad (1)$$

$$S_k(t) = \Pi(t) \exp(j2\pi f_k t) \quad (2)$$

$$\Pi(t) = \begin{cases} 1, & (0 < t \leq T_s) \\ 0, & (t \leq 0, t > T_s) \end{cases} \quad (3)$$

Where ' C_{ki} ' is the i^{th} information symbol at the k^{th} subcarrier, S_k is the waveform for the k^{th} subcarrier, ' N_{sc} ' is the number of subcarriers, ' f_k ' is the frequency of the subcarrier, and ' T ' is the symbol period. The optimum detector for each subcarrier can use a filter that matches the subcarrier waveform, or a correlator matched to the subcarrier as in Fig. 1. Therefore, the detected information symbol ' C_{ik} ' at the output of the correlator is given by

$$\begin{aligned} C'_{ki} &= \int_0^{T_s} r(t - iT_s) S_k^* dt \\ &= \int_0^{T_s} r(t - iT_s) \exp(-j2\pi f_k t) dt \end{aligned} \quad (4)$$

Where ' $r(t)$ ' is the received time-domain signal. The basic MCM uses non-overlapped band limited signals, and can implemented using a bank of large number of oscillators and filters at both transmit and receive end. The major disadvantage of MCM is that it requires large bandwidth. In order to design the filters and oscillators cost-efficiently, the channel spacing should be multiples of the symbol rate which in turn reduces the spectral efficiency.

A novel approach called OFDM is investigated including overlapped but orthogonal signal set [19]-[20]. This orthogonality generates from the straightforward correlation between any two subcarriers, given by

$$\begin{aligned} \delta_u^t &= \frac{1}{T_s} \int_0^{T_s} S_k S_l^* dt \\ &= \frac{1}{T_s} \int_0^{T_s} \exp(j2\pi(f_k - f_l)t) dt \end{aligned} \quad (5)$$

$$= \exp(j\pi(f_k - f_l)T_s) \frac{\sin(\pi(f_k - f_l)T_s)}{\pi(f_k - f_l)T_s} \quad (6)$$

Fig. 1: Generic Implementation of Multi Carrier Modulation (MCM) System

It can be seen that if the following condition

$$f_k - f_l = m \frac{1}{T_s} \quad (7)$$

is satisfied, then the two subcarriers are orthogonal to each other. This implies that these orthogonal subcarrier sets, with their frequencies spaced at multiple of inverse of the symbol rate can be recovered with the matched filters (Eq. 4) without inter-carrier interference (ICI), in spite of strong signal spectral overlapping.

B. Principle of Coherent Optical OFDM

Because of its strong resistance to the channel dispersion, OFDM is actively utilized for applications in the optical domain. The most critical assumption for OFDM is the linearity in modulation, transmission, and demodulation. As a result, a linear transformation is the key goal for the OFDM implementation. A generic optical OFDM system can be divided into five functional blocks including (i) the RF OFDM transmitter, (ii) the RF-to-optical (RTO) up-converter, (iii) the optical channel, (iv) the optical-to-RF (OTR) down-converter, and (v) the RF OFDM receiver [21]. The RF OFDM transmitter/receiver generates/recovers the OFDM signals either in baseband or RF band. It is apparent that the challenges for CO-OFDM implementation are to obtain a linear RTO up-converter and linear OTR down-converter.

It has been analyzed that by biasing the Mach-Zehnder modulators (MZMs) at null point, a linear conversion between the transformation from optical field signal to RF (or electrical) signal can be achieved [21], [23]-[24]. Now by putting together such a composite system cross RF and optical domain [21]-[22], a linear channel can be constructed where OFDM can perform its best, i.e., mitigating channel dispersion impairment, in both RF domain and optical domain.

C. Optical Spectral Efficiency for CO-OFDM

In CO-OFDM systems, ' N_{sc} ' subcarriers are transmitted in every OFDM symbol period of ' T_s ', the total symbol rate ' R ' for CO-OFDM systems is given by

$$R = \frac{N_{sc}}{T_s} \quad (8)$$

The OFDM bandwidth ' B_{OFDM} ' is given by

$$B_{OFDM} = \frac{2}{T_s} + \frac{N_{sc}-1}{t_s} \quad (9)$$

Where ' t_s ' is the observation period. If a large number of subcarriers are used, the bandwidth efficiency of OFDM ' η ' is found to be

$$\eta = 2 \frac{R}{B_{OFDM}} = 2\alpha, \alpha = \frac{t_s}{T_s} \quad (10)$$

The factor of '2' represents for two polarizations in the fiber. Using a typical value of 8/9 [19], we obtain the optical Spectral efficiency factor η of 1.8 Baud/Hz. The optical spectral efficiency gives 3.6 bit/Hz if QPSK modulation is used for each subcarrier. The spectral efficiency can be further improved by using higher-order QAM modulation [25].

Table 1: Simulation Parameters

Laser frequency	193.1THz
Laser power	10 dBm
Fiber Attenuation	0.2 dB/km
Fiber length	250 km
Fiber dispersion	16.75 ps/nm/km
Differential group delay	0.2 ps/km
Max. nonlinear phase shift	3 mrad

In the RF OFDM transmitter, the input data is split into multiple parallel branches. This is called as “serial-to-parallel” conversion. The number of the multiple branches equals to the number of subcarriers. Then the converted signal is mapped on to quadrature amplitude modulation (QAM). The IFFT is used to convert the mapped signal from frequency domain into time domain. Two-dimensional complex signal is used to carry the information. A pair of electrical low-pass filters is used to remove the alias sideband signal.

At the RTO up-converter, the baseband OFDM signal is

up shifted onto optical domain using an optical I/Q modulator, which is comprised by two Mach-Zehnder modulators (MZMs) with a 90° optical phase shifter. The unconverted OFDM signal in optical domain is given by

$$E(t) = \exp(j\omega_{LD1}t + \phi_{LD1}) S_B(t) \quad (11)$$

Where ' ω_{LD1} ' and ' ϕ_{LD1} ' are the frequency and phase of the transmitter laser, respectively and $S_B(t)$ is the baseband OFDM. The optical signal ' $E(t)$ ' is applied into the optical fiber link, with an impulse response of ' $h(t)$ '. The received optical signal ' $E'(t)$ ' becomes

$$E'(t) = \exp(j\omega_{LD1}t + \phi_{LD1}) S_B(t) * h(t) \quad (12)$$

Table 2: Simulation Parameters

Photodetector responsivity	1 A/w
Photodetector dark current	10 nA
Photodetector center frequency	193.1THz
Fiber length	250 km
Photodetector sample rate	5Hz
Photodetector thermal noise	10^{-22} w/Hz

Fig. 2: Block Diagram of Coherent Transmitter and Receiver

Fig. 3: 1 Gbps OFDM MZM Generated Output

Fig. 4: (a) 1Gbps OFDM Demodulator in-phase Output.
(b) 1Gbps 4-QAM CO-OFDM Received Constellation Diagram

Fig. 5: 20Gbps OFDM Modulated MZM Output

Fig. 6: (a) 20 Gbps OFDM Demodulator in-phase Output.
(b) 20 Gbps CO-OFDM Received Constellation Diagram

Fig. 7: 100Gbps 4-QAM OFDM Generated Output

Fig.8: (a) 100Gbps Demodulated OFDM Output. (b)
100Gbps 4 QAM -OFDM Received Constellation Diagram

III. RESULTS AND DISCUSSION

Figure 3 and 4 show the received plot of the constellation spread of amplitudes and phases in a conventional 4 QAM CO-OFDM system for datarate of 1Gbps. It shows that the constellations of the QAM symbols are tightly grouped. Fig.5and 6 shows the received plot of the constellation spread of amplitude and phases in a 4 QAM CO-OFDM with 20Gbps datarate. Fig.7and 8 shows the generated 100Gbps 4 QAM-CO-OFDM spectrum and received constellation spread of 100Gbps datarate. The phase noise is caused by fiber nonlinearity induced inter-carrier interference (ICI).

Results show that as data rates increases, the amplitude and phase noises of the received OFDM spectrum system are also increases. This is due to the nonlinearities in the optical fiber, shot noise and thermal noise of photo detectors at the receiver.

IV. CONCLUSION

The performance of Coherent Optical OFDM (CO-OFDM) is analyzed for different data rates such as 1Gbps, 20Gbps and 100Gbps. 4 QAM-OFDM is modulated using MZM and transmitted through the fiber for a distance of 250 km. Due to the different nonlinearities of fiber and photo detector, the signal is distorted. At the receiver end the filtered optical signal is converted to electrical signal and OFDM is demodulated. Results show that at the receiver, as the data rates increases the distortions of the OFDM spectrum and QAM constellations also increases.

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