Investigation of I/Q Imbalance in Coherent Optical OFDM System

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Abstract—The inphase/quadrature (I/Q) amplitude and phase imbalance effects are studied in coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems. An analytical model for the I/Q imbalance is developed and supported by simulation results. The results indicate that the I/Q imbalance degrades the BER performance considerably.

Keywords—Coherent detection, I/Q imbalance, OFDM, optical communications

I. INTRODUCTION

The trend toward the reconfigurable optical networks with high transport speeds poses some challenges to the network design. For example, the signal has become extremely sensitive to the chromatic dispersion (CD), polarization mode dispersion (PMD), filtering effects of add/drop multiplexers, and the imperfection of the optoelectronic components [1]. Therefore, it is mandatory that the per-channel optical dispersion compensation is used. Furthermore, to support long-haul transmission in the range of 1000 km, even the best fiber link requires PMD compensation for high transmission speeds. Optical PMD compensators are bulky, lossy, and expensive. As such, an adaptive optical transmission system for an agile and reconfigurable optical network is essential to support high capacity and ever-evolving user demands. Optical orthogonal frequency division multiplexing (O-OFDM) systems have recently been proposed to satisfy all the above-mentioned requirements for the flexible optical transmission networks which are needed for today and future applications [2], [3].

Recently, there is increasing interest in coherent optical OFDM (CO-OFDM) system which is a promising technology for long-haul and high-speed optical transmission systems. It combines the advantages of both coherent detection and OFDM scheme to improve power and spectral efficiency, and to facilitate flexible impairment compensation using digital signal processing (DSP) [4], [5]. This gives the system its superior performance that makes it the best candidate to the next generation of optical transmission systems.

A simplified analysis of OFDM scheme assumes linearity among all the system stages between the transmitter inverse fast Fourier transform (IFFT) and receiver FFT. The nonlinearity or imbalance in signal components in any part of the system causes performance degradation due to intersymbol interference (ISI) and/or intercarrier interference (ICI) effects. One of these nonlinearities that can affect the performance is the mismatch between the inphase (I) and quadrature phase (Q) components of the complex OFDM signal, the “I/Q imbalance” [6], [7]. This imbalance can be in the phase and/or the amplitude of the I and Q components of the OFDM signal.

Many parts of the system can contribute in inducing the imbalance between the I and Q parts of the optical OFDM signal. The imbalance can be induced by the RF and/or the optical components of the system. For example, the imbalance can be produced by the imperfection or bias deviation in the digital-to-analog converters (DACs)/analog-to-digital converters (ADCs), the imperfection in the optical splitters in the transmitter or receiver sides, the difference in the insertion loss value between the two Mach-Zehnder modulators (MZMs) of the I/Q optical modulator at the transmitter [8], and the imperfection or imbalance in splitting the power in the optical hybrid of the CO-OFDM receiver [9]. The I/Q imbalance induced at the transmitter side causes image interference from the subcarriers symmetrical with respect to the transmitter laser, and similarly receiver-side I/Q imbalance causes image interference among symmetrical subcarriers with respect to the local oscillator. As a result, each constellation point is deformed and spread due to random interference from symmetrically opposite subcarrier. This ICI is one of the challenges against using higher-order constellations to achieve high spectral efficiency in CO-OFDM systems.

In this paper, the I/Q imbalance and its effects on the performance of CO-OFDM system are studied and explained, and a mathematical model including amplitude and phase imbalance is developed. Simulation results for I/Q imbalance are presented using "OptiSystem Ver. 9" software package and the results are used to elucidate the influence of imbalance on system performance and to determine the relation between the formulated imbalance parameters and transmission bit error rate (BER).

II. COHERENT OPTICAL OFDM

A generic O-OFDM system is depicted in Fig. 1. It consists of five basic functional blocks: (i) RF OFDM transmitter, (ii) RF-to-optical (RTO) up-converter, (iii) optical channel, (iv) optical-to-RF (OTR) down-converter, and (v) RF OFDM receiver.

Optical OFDM is a special form of optical MCM techniques, employing overlapped orthogonal signal set, with an increased spectral efficiency.
As shown in Fig. 1, the input digital data to the RF OFDM transmitter is serial-to-parallel converted into blocks of bits consisting of $N_{sc}$ information symbols; each may comprise multiple bits for m-ary coding. These information symbols are mapped into two-dimensional complex signal $C_k$, where $C_k$ represents the mapped information symbol to be modulated on the $k$th subcarrier at the $i$th instant. The inverse discrete Fourier transform (IDFT) is applied to the $i$th set of $C_k$ symbols to produce the time-domain samples of the $i$th “OFDM symbol”, utilizing the computationally-efficient FFT algorithm. A guard interval is then inserted to avoid channel dispersion. The resulting baseband OFDM signal $s_b(t)$ can be expressed as [10]

$$s_b(t) = \sum_{i=-\infty}^{\infty} \sum_{k=-N_{sc}/2}^{N_{sc}/2} C_k \Pi(t - iT_s) - iT_s \exp(j2\pi f_k (t - iT_s)) \quad (1a)$$

$$f_k = \frac{k - 1}{T_s} \quad (1b)$$

$$\Pi(t) = \begin{cases} 1, & (-\Delta_t < t < t_c) \\ 0, & \text{otherwise} \end{cases} \quad (1c)$$

where $N_{sc}$ is the number of OFDM subcarriers, $T_s$ is the OFDM symbol period, $f_k$ is the frequency of the $k$th subcarrier, $\Delta_t$ is the guard interval length, and $t_c$ is the observation period during which the OFDM symbol is to be captured at the receiver, and $\Pi(t)$ is the rectangular pulse waveform of the OFDM symbol.

The digital OFDM signal is converted to analog form through DACs and filtered with low-pass filters (LPFs) to remove the unwanted alias sideband signals. The baseband OFDM signal is then either converted into an IF signal, by an I/Q modulator, and then to optical domain, or directly converted to the optical domain, depending on the system configuration [11]. At the receiver end, the baseband OFDM signal is sampled by ADCs, and demodulated by performing the discrete Fourier transform (DFT) and baseband signal processing to recover the data.

In CO-OFDM the electric field spectrum of the transmitted optical signal is a replica of the baseband RF OFDM signal, with no need for any optical carrier component to be transmitted. Instead, the carrier component needed for OTR-conversion is locally generated at the receiver.

Fig. 2 shows the conceptual diagram of a direct up/down conversion architecture for CO-OFDM systems [11], [12]. In direct RTO up conversion, the RTO is simply an optical I/Q modulator comprising two MZMs to convert the I and Q components of the baseband OFDM signal to the optical domain directly. In the direct down conversion architecture, the OTR converter uses two pairs of PD receivers and optical hybrids to perform optical to electrical I/Q detection.
\[ E_{LO} = E'_L + E_N \]

where \( E_N \) is the intensity noise and \( E'_L \) is the LO field in the presence of intensity noise. The same fashion used in (3) can be used for \( E'_L \) to describe the imbalance parameters to form

\[ E'_L = E_L + j e^{j \vartheta} G_E E_L \]

(6a)

\[ = [E_{Li} - (1 - a_c) \sin \vartheta_E E_{Li}] + j(1 - a_c) \cos \vartheta_E E_{Li} \]

(6b)

where \( G_r \) and \( \vartheta_r \) are the amplitude and phase imbalance parameters for the receiver side, respectively. From this, the LO signal field in absence of both I/Q imbalance and intensity noise can be expressed as

\[ E_L = E_{Li} + j E_{Le} \]

where \( E_{Li} \) and \( E_{Le} \) are the real and imaginary parts of \( E_L \), respectively.

The output signals \( E_{1-4} \) of the 6-port optical hybrid are given by [13]

\[ E_1 = \frac{1}{\sqrt{2}} [E_L + E_{LO}] \]

(8a)

\[ E_2 = \frac{1}{\sqrt{2}} [E_L - E_{LO}] \]

(8b)

\[ E_3 = \frac{1}{\sqrt{2}} [E_L - j E_{LO}] \]

(8c)

\[ E_4 = \frac{1}{\sqrt{2}} [E_L + j E_{LO}] \]

(8d)

where in writing (8a)- (8d) it is assumed that the hybrid is lossless.

The corresponding photocurrents generated at the photodiodes can be found by the square rule as

\[ I_{PD1} = |E_1|^2 = \frac{1}{2} [E_{Li}^2 + E_{LO}^2 + 2 \text{Re}(E_E E_{LO}^*)] \]

(9a)

\[ I_{PD2} = |E_2|^2 = \frac{1}{2} [E_{Li}^2 + E_{LO}^2 - 2 \text{Re}(E_E E_{LO}^*)] \]

(9b)

\[ I_{PD3} = |E_3|^2 = \frac{1}{2} [E_{Li}^2 + E_{LO}^2 + 2 \text{Im}(E_E E_{LO}^*)] \]

(9c)

\[ I_{PD4} = |E_4|^2 = \frac{1}{2} [E_{Li}^2 + E_{LO}^2 - 2 \text{Im}(E_E E_{LO}^*)] \]

(9d)

where \( \text{Re}(\cdot) \) and \( \text{Im}(\cdot) \) represent the real and imaginary parts of the argument, respectively; and the responsivity is assumed to have unity value for all photodiodes for simplicity. Further [13]

\[ |E_{Li}|^2 = |E_{Li}|^2 + |E_{ASB}|^2 + 2 \text{Re}(E_E E_{ASB}^*) \]

(10a)

\[ |E_{LO}|^2 = I_{LO}(1 + I_{RIN}) \]

(10b)

where \( I_{LO} \) and \( I_{RIN} \) are the average power and relative intensity noise (RIN) of the local laser, respectively.

The real and imaginary parts of the OFDM signal represented by the photocurrents \( I \) and \( Q \), respectively, can be obtained by the first and second pairs of balanced detectors; that is

\[ I_i = I_{PD3} - I_{PD2} = I_{Io} + \Delta I_i \]

(11)

where \( I_{Io} \) represents the OFDM I-component in the absence of I/Q imbalance and \( \Delta I_i \) represents the change in the I component photocurrent introduced by the presence of I/Q imbalance. These can be expressed as

\[ I_{Io} = 2(E_{rI} E_{Li} + E_{rI} E_{Li}) = 2 \text{Re}(E_E E_{Li}^*) \]

(12)

and

\[ \Delta I_i = 2\left[ (G_r \cos(\vartheta - \vartheta_r) - 1) E_{rI} E_{Li} - G_s \sin(\vartheta - \vartheta_r) E_{rI} E_{Li} \right] \]

(13)

For a perfectly balanced system, (i.e., \( G_r = G_s = 1, \vartheta_r = 0 \)), \( \Delta I_i \) reduces to zero. It is worth to note that the balance detection suppresses the noise terms described in (10a) and (10b).

Similarly, the photocurrent representing the OFDM Q-component can be expressed as

\[ I_Q = I_{PD3} - I_{PD4} = I_{Qo} + \Delta I_Q \]

(14)

where

\[ I_{Qo} = 2(E_{rI} E_{Li} + E_{rI} E_{Li}) = 2 \text{Im}(E_E E_{Li}^*) \]

(15)

and

\[ \Delta I_Q = 2\left[ 1 - G_s \cos(\vartheta - \vartheta_r) \right] E_{rI} E_{Li} - \left[ 1 - G_r \cos(\vartheta - \vartheta_r) \right] E_{rI} E_{Li} + G_s G_r \sin(\vartheta - \vartheta_r) E_{rI} E_{Li} \]

(16)

Here, \( I_{Qo} \) represents the Q component of the OFDM signal in the absence of I/Q imbalance, which changes by \( \Delta I_Q \) when the imbalance exists.

The complex OFDM signal is represented by the complex photocurrent \( \vec{I} \) consisting of both \( I \) and Q components; that is

\[ \vec{I} = I + j I_Q = \vec{I}_o + \Delta \vec{I} \]

(17)

\[ \vec{I}_o = 2(E_{rI} E_{Li} + E_{rI} E_{Li}) + j(E_{rI} E_{Li} - E_{rI} E_{Li}) \]

\[ = 2(E_E E_{Li}^*) \]

(18)

\( \vec{I}_o \) is the complex photocurrent at perfect I/Q balance condition and it is in essence a linear replica of the incoming complex signal that is frequency down-converted by a LO frequency.

It is worth to examine (13) and (16) when only phase imbalance exists (i.e., \( G_r = G_s = 1 \)). In this case \( \Delta I_i \) and \( \Delta I_Q \) read

\[ \Delta I_i = 2(\cos(\vartheta - \vartheta_r) - 1) E_{rI} \]

(19a)

\[ \Delta I_Q = 2(1 - \cos(\vartheta - \vartheta_r)) E_{rI} E_{Li} - \sin(\vartheta - \vartheta_r) E_{rI} E_{Li} \]

(19b)

Investigating (19a) and (19b) reveals that the I/Q phase imbalance induced at the transmitter cannot be compensated by introducing I/Q phase mitigation mismatch at the receiver. This is clear since \( \Delta I_i \) and \( \Delta I_Q \), defined in (4.18a) and (4.18b), respectively, do not reduce to zero when \( \vartheta_r \) is.

IV. SIMULATION RESULTS

The CO-OFDM system under investigation is shown in Fig. 2. The system uses direct up/down conversion method. Unless otherwise stated, the parameters values used in the simulation are listed in Table I. The system uses standard single-mode fiber with in-line Erbium-doped fiber amplifiers (EDFAs) to compensate fiber loss.
TABLE I

PARAMETERS VALUES USED IN SIMULATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit rate</td>
<td>10 Gb/s</td>
</tr>
<tr>
<td>Central wavelength/frequency</td>
<td>1552.52 nm / 193.1 THz</td>
</tr>
<tr>
<td>Coupling ratio of transmitter and receiver X-couplers</td>
<td>0.5</td>
</tr>
<tr>
<td>Differential group delay</td>
<td>0.2 ps/km</td>
</tr>
<tr>
<td>Dispersion parameter, D</td>
<td>16.75 ps/(km-nm)</td>
</tr>
<tr>
<td>Fiber attenuation</td>
<td>0.2 dB/km</td>
</tr>
<tr>
<td>Gain of inline optical amplifier after each nominal span</td>
<td>20 dB</td>
</tr>
<tr>
<td>Linewidth of transmitter and LO LDs</td>
<td>150 kHz</td>
</tr>
<tr>
<td>LO optical power</td>
<td>0 dBm</td>
</tr>
<tr>
<td>Modulation type</td>
<td>QPSK</td>
</tr>
<tr>
<td>MZMs extinction ratio</td>
<td>60 dB</td>
</tr>
<tr>
<td>MZMs insertion loss</td>
<td>1 dB</td>
</tr>
<tr>
<td>MZMs switching bias voltage</td>
<td>4 V</td>
</tr>
<tr>
<td>Number of FFT points</td>
<td>1024</td>
</tr>
<tr>
<td>Number of OFDM subcarriers, Nsc</td>
<td>512</td>
</tr>
<tr>
<td>Noise figure of in-line amplifiers</td>
<td>4 dB</td>
</tr>
<tr>
<td>Nominal fiber single-span length</td>
<td>100 km</td>
</tr>
<tr>
<td>Power launched to the fiber</td>
<td>-10 dBm</td>
</tr>
<tr>
<td>Receiver PDs dark current</td>
<td>10 nA</td>
</tr>
<tr>
<td>Receiver PDs responsivity</td>
<td>1 A/W</td>
</tr>
<tr>
<td>Receiver PDs thermal noise</td>
<td>$1 \times 10^{-22}$ W/Hz</td>
</tr>
<tr>
<td>Transmitter LD optical power</td>
<td>0 dBm</td>
</tr>
<tr>
<td>Transmitter optical booster gain</td>
<td>11 dB</td>
</tr>
</tbody>
</table>

The RTO up-converter (the I/Q optical modulator) is built up using an X-coupler, two Mach-Zehnder modulators, and an optical combiner. The optical signal from the laser source is applied to the 1st input port of the coupler to yield the I and Q carrier components, at the output ports, which are fed to the MZMs, as shown in Fig. 3. Lithium Niobate MZM (LiNb-MZM) with dual-drive type is used. Each MZM is driven by the positive and negative signals of one of the components of the baseband OFDM signal (I or Q) at the two inputs of modulating signal of the MZM. The output signals from the two MZMs are combined by the optical combiner to form the complex optical OFDM signal to be amplified and transmitted.

The OTR down-converter is built up using four X-couplers, a 90° phase shifter, four PIN photodetectors, and two electrical subtractors, as shown in Fig. 4. This OTR conversion network employs balanced detectors for noise cancellation.

To induce an I/Q amplitude imbalance in the system, an optical gain component is used in the simulation to change the amplitude of the field of optical signal in the Q-branch of the LO signal before being fed to the optical hybrid. The scaling imbalance parameter, $G_r$, can then be varied in this branch to induce an amplitude imbalance between the I and Q branches of the LO signal as desired.

![Fig. 3 Direct up-converter built for simulation](image1)

![Fig. 4 Direct down-converter built for simulation](image2)
mentioned before, the imbalance may come from electrical or the optical components of the system. When the imbalance is induced by some electrical part, the change in the signal amplitude in one of the two branches does not affect the signal in the other branch. Whereas when the imbalance is induced by some optical component and the optical signal level is changed in one branch, the signal level in the other branch may and may not get influenced, depending on the reason of the optical amplitude imbalance. For example, if the imbalance occurs due to the difference in the insertion loss of the two (I- and Q-branch) MZMs, that is if the insertion loss of one of the MZMs is changed, the signal level at the output of the other MZM does not change. This is true since the two branches are independent. But if the imbalance is caused by some optical splitter (due to aging or thermal effects) the decrement in the signal level at one branch will correspond an increment in the signal level at the other branch. For investigating the effect of the latter case on system performance, which has more complexity, let us consider the above-mentioned scaling parameter $G_{rQ}$ as the scaling factor for the signal level at the Q-branch of the LO signal, and denote it as $G_{rQ}$. And assume that the scaling parameter at the I-branch is $G_{rI}$.

Assuming that the split components in the system are lossless, the value of total output optical power from the two ports of the split device is constant regardless of the split ratio. That is

$$ P_I + P_Q = \text{constant} \hspace{1cm} (20) $$

where $P_I/P_Q$ represents the optical power at the I-/Q-branch. From which

$$ G_{rI}^2 + G_{rQ}^2 = 2 \hspace{1cm} (21a) $$

or

$$ G_{rI} = \sqrt{2 - G_{rQ}^2} \hspace{1cm} (21b) $$

Let us define a new imbalance parameter $B$, where

$$ B = 1 - \frac{G_{rQ}}{G_{rI}} \hspace{1cm} (22) $$

This parameter has a value of zero when the powers at the two branches are equal.

Fig. 6 shows the transmission BER as a function of $B$ for different link lengths. As expected, the system performance degrades as the imbalance parameter increases. In the absence of imbalance ($B = 0$), BERs of $2.3 \times 10^{-4}$, $6.1 \times 10^{-5}$, $2.3 \times 10^{-4}$, and $5.1 \times 10^{-4}$ are obtained when the link lengths are 1300, 1500, 1700, and 1900 km, respectively. These values are to be compared with BERs of $8.4 \times 10^{-5}$, $2.4 \times 10^{-4}$, $4.3 \times 10^{-4}$, and $9.3 \times 10^{-4}$, respectively, when amplitude imbalance exists in the system with $B = 0.2$.

The constellation diagrams of the received signal for the link of 1700 km at $B = 0$ and $B = 0.4$ ($G_{rQ} = 0.73$, $G_{rI} = 1.21$) can be seen in Fig. 7.
BER value is $2.3 \times 10^{-5}$, $6.1 \times 10^{-5}$, $2.3 \times 10^{-4}$, and $5.1 \times 10^{-3}$ with ideal balance; but in the presence of phase imbalance of 6°, the BER increases to $6.9 \times 10^{-5}$, $1.9 \times 10^{-4}$, $5.3 \times 10^{-4}$, and $9.2 \times 10^{-4}$ when the length of the link is 1300, 1500, 1700, and 1900 km, respectively.

REFERENCES