An ICI Reduction based on PAPR Clipping in Coherent Optical OFDM System

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Abstract— **The Inter-Carrier Interference (ICI) compensation for Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) system has been studied in this paper. The purpose behind is to investigate the presence of ICI due to the impact of Laser Phase Noise (LPN) and Fiber Non-Linearity (FNL). Thereby, we propose a simple clipping scheme which represents an effective distortion algorithm to decrease the Peak to Average Power Ratio (PAPR) for 4QAM system. The method exhibits a significant process on ICI cancellation in CO-OFDM system. The OFDM signal is basically transmitted along 550km distance rated at 10Gbps single mode fiber for the coherent optical mode. The new findings show that the receiver sensitivity is highly improved below 10^{-3} FEC for laser power 5dBm; and archives about 1dBm to 2.4dBm when laser power becomes 8dBm at a typical clipping ratio of 0.6. In particular, the system exhibits a good performance over a 385km transmission distance in comparison to the conventional CO-OFDM. As a result, the proposed clipping shows that the system can enhance its the performance by reducing ICI in the CO-OFDM system; in addition to present a high robustness in BER metric against FNL by a clear reduction in PAPR.**

Keywords— ***Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM), Inter-Carrier Interference (ICI), Peak to Average Power Ratio (PAPR), Laser Phase Noise (LPN), Fiber Nonlinearity (FNL), Bit Error Rate (BER).***

I. INTRODUCTION

Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) has yet an attractive attention in optical communications [1],[2]. However, in spite of the fact that CO-OFDM systems have great advantages over others Optical OFDM systems like direct-detection OFDM, the transmitted optical OFDM signal is sturdy against ICI and inter-symbol interference (ISI) caused by polarization-mode dispersion (PMD) and chromatic dispersion(CD) in optical fiber cable [3],[4].

In Comparison with DD-OOFDM systems, the CO-OFDM system is considered to be suitable for long-haul transmission at the rate of tens and hundreds of gigabits due to its higher spectral and power efficiency[5],[6],[7].

Likewise, the CO-OFDM is very susceptible to the phase noise induced by laser source, the FNL and the variation in laser frequency offset which totally impact on the system performance[8]. Furthermore, all these factors can cause an increase ICI in the system and drastically degrade the receiver sensitivity [9]. In effect, ICI acts like an Additive White Gaussian Noise (AWGN) whereas the carrier phase error can turn the phase of all constellation diagram points in a joint direction. As a result, Inter-sub-carrier crosstalk will cause coherent interference among adjoining sub-carriers. Notably, this can be seen as a type of ICI. Meantime, the presence of self phase modulation (SPM) can turn the phase of the sent signal in a common direction; so the action is categorized as same as the carrier phase noise.

Nevertheless, It is familiar to notice that the phase noise participated by the sender laser and receptor laser will notably lead to impairment the activity of CO-OFDM systems. Thus the optical OFDM system can be susceptible to the FNL due to the high PAPR of the OFDM signal. The impact of FNL is mainly considered somewhat similar to that of LPN [10]. Therefore, some methods have been proposed recently to combat ICI through eliminating the laser phase noise. Moreover, In[11] a discussion has been made to the practicability of zero-overhead LPN compensation for long haul CO-OFDM systems. In other words, they utilize the decision-directed phase equalizer which refreshes the equalization parameters on a symbol-by-symbol basis after a primary decision making stage and recuperates an estimation of the LPN value. Then again, this can happen by separating and averaging the phase drift of all OFDM sub-channels. In this manner, a second equalization is performed by utilizing the estimated phase noise value which is followed by an ultimate choice making stage.

Moreover, the researchers compared the performance of the decision-directed phase equalizer (DDPE) and the CO-OFDM traditional equalizer for various laser line width values after transmission more than 2000 km of single-mode fiber (SMF) at 40 Gb/s. In addition, there is an attempt to find out the impact of FNL on the received signal quality. Another key thing to remember is that in [12] a comparison has been made between the pilot and data aided phase evaluation methods for a CO-OFDM transmission experiment at 8 Gb/s over 1000-km SMF without optical dispersion compensation. It has been shown that five subcarriers are appropriate for pilot-aided phase evaluation.

Conversely, other methods have also been investigated to combat nonlinearity in the CO-OFDM [13, 14]. One of the previously mentioned methods depends on PAPR reduction method which can also combat the impact of LPN, FNL and consequently lead to reduce the effect of ICI as in[15].

In this paper, a simple algorithm of clipping process has been proposed (which is the simplest algorithm) in order to reduce PAPR in the CO-OFDM. The method is employed to decrease the impact of FNL and the LPN as well. This algorithm has been verified for several values of the Clipping Ratio(CR) in order to specify the best value of CR which is required for designing more robust CO-OFDM system with a good performance. The results clearly reveal that the clipping-based system can outperform the conventional CO-OFDM system through different metrics of quality factor, EVM and BER.

The remainder of this paper is organized as follows. Section II presents the basic optical fiber impairments; while Section III reviews the CO-OFDM system, PAPR concept and the Complementary Combined Distribution Function (CCDF). In Section IV, the proposed clipping technique is described for PAPR reduction. The simulation results of clipping-based CO-OFDM system are demonstrated in Section V. The last section is the conclusion

II. BASIC IDEA OF OPTICAL IMPAIRMENTS

Let X(k) be the OFDM sent signal for the k-th subcarrier, then the R(k) for kth subcarrier which is the received OFDM signal after Fast Fourier Transformer(FFT) is shown as[16]:

$$R_k = X_k \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \exp(j\varnothing(n))$$
$$+ \frac{1}{N} \sum_{n=0}^{N-1} \sum_{k=0}^{N-1} X(k).\exp(j\varnothing(n)).\exp(-j2\pi n(L-k)/N) \qquad (1)$$

Where L≠K and N is the number of subcarrier. It is worth mentioning that the first part of the equation represented the phase error rotation, whereas the second part is represent the ICI caused by L subcarriers. When the LPN and FNL impairments are increased in the system, this will cause phase rotation in the received signal, ICI between Sub-Carriers, interference between the main carrier and Sub-Carriers and ISI especially when the power for the signal is high. In other words, the main job is to compensate the effect of these impairments on the signal.

III. CO-OFDM SYSTEM

Figure 1 represents a general block diagram of OFDM technique which is applied in optical communication due to its attractive properties in the long haul transmission. Additionally, OFDM is a multi-carrier-modulation (MCM) technique where the sub carriers are reciprocally orthogonal to one another. The main precept of OFDM comprises the transformation of a sequent data flows into a set of parallel data flows of extended time duration. In OFDM sender part, the data is first turned into symbol using any constellation like QAM or PSK mapping and then, it can be modulated into the subcarriers using IFFT modulator, adding cyclic prefix(CP) then change to serial form in order to obtain the OFDM spectrum. The OFDM signal is divided into in-phase component I and quadrature component Q. To that end, the I and Q is converted and modulated to optical frequency using IQ modulator in the optical transmitter section. The I and Q is then converted and modulated to optical frequency using IQ modulator in the optical transmitter section. The IQ modulator consists of one Continuous wave laser which produces the optical carrier. Also there are two Mach-Zehnder modulators with a 90 degree phase offset which converted the electrical signal in to optical signal in order to send it through the optical channel. The optical channel consist of standard single mode fiber, dispersion compensating fiber(DCF) and optical amplifier. The optical receptor section converts optical signal in to radio frequency uses an optical 90° hybrid and two pairs of balanced detectors to obtain the I/Q components of OFDM signal. Then again, it is followed by the OFDM receptor part which is used to demodulate and recover the original signal.

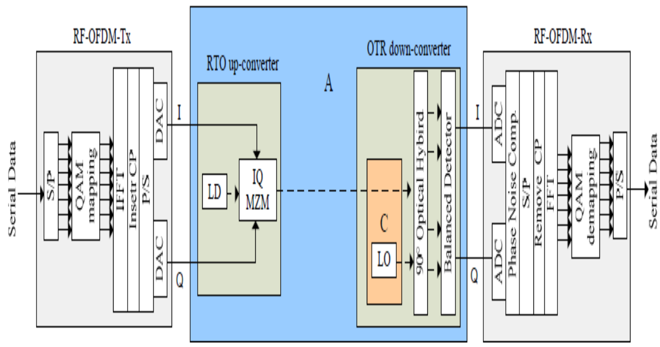


Fig.1. Block Diagram of Optical OFDM[17]

With this system, OFDM signal is comprised a substantial quantities of balanced sub carriers. Coherent addition of (N) subcarriers that have same phase will create top power (N) duplicate by the normal power. On the other hand, a huge PAPR increases the FNL impairment which diminishes the performance of the system. Furthermore, the existence of a large number of multi-modulated sub-carriers in the OFDM signal results in the power being high if it is different and normal for the entire signal.

OFDM contains a block of N data flow U_k (k=0,1,..,N-1), of vector U, which will be sent in side by side. One OFDM data symbol is given by:

$$u(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} U_k e^{j2\pi f_k t} \qquad (2)$$

Where f_k is the subcarriers frequency. PAPR is being an irregular variable, since it is relying upon the input information, which is likewise an arbitrary variable. In this manner, PAPR can be computed by finding the proportion between peak power to the average number of times that the envelope of a signal crosses a given level[18]. Then the equation of PAPR can be written as:

$$PAPR = \frac{\max[|u(t)|^2]}{E[|u(t)|^2]} \qquad (3)$$

Where $E[|u(t)|^2]$ is the average value of OFDM symbol. Similarly, the cumulative distribution function (CDF) is considered a standout that is distinguished among the most frequently utilized parameters, which is utilized to gauge the proficiency of any PAPR technique.

Regularly, the complementary CDF (CCDF) is utilized rather than CDF. That is to say that it is utilized in order to quantify the probability that the PAPR of a specific information block overrides the given ledge. Thus the CCDF of PAPR can be expressed as [19]:

$$DP(PAPR > z) = 1 - (1 - e^{-z})^N \qquad (4)$$

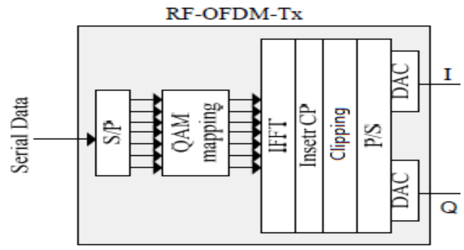
IV. The Proposed Clipping Technique

As previously mentioned, the ICI and its effect can be reduced by the way of eliminating the impact of impairments. Moreover, this can be done by reducing the PAPR of the CO-OFDM system. It has been noticed that there are numbers of approaches that have been proposed to deal with the PAPR problem in order to mitigate the FNL in the CO-OFDM. That is to say, these techniques include amplitude clipping [20], clipping and filtering, tone reservation (TR) [21], partial transmit sequence (PTS) [22] and selected mapping (SLM) [23]. In this paper, clipping has been used in order to reduce PAPR. In another way, Clipping is efficient, simple and uncomplicated technique to reduce PAPR. Table(1) shows a comparison between clipping algorithm with others algorithm that used to reduce PAPR[24],[25].

TABLE .1. COMPARSION OF DIFERENT PAPR REDUCTION TECHNIQUES

Technique	BW Increase	Side Info.	Averg. Power Increase	Complexity
clipping	No	No	No	Low
PTS	Yes	Yes	No	High
SLM	Yes	Yes	No	High
TR	Yes	No	Yes	High
companding	Yes	Yes	No	High

Next, to illustrate the proposed system, Figure(2) shows the block diagram of the OFDM transmitter after adding clipping technique.



.Fig.(2)OFDM Transmitter with Clipping Algorithm

Moreover, the signal is restricted to the set threshold in this technique when the peaks of the input signal exceed a particular threshold. Generally, the signal goes through directly if the input signal dose not exceed a particular threshold . The clipping equation can be written as:

$$y(n) = \begin{cases} -A & \text{if } u(n) < -A \\ u(n) & \text{if } -A < u(n) < A \\ A & \text{if } u(n) > A \end{cases} \qquad (5)$$

Where u_n denotes OFDM signal and A is being the threshold amplitude of the signal. We can define the CR as in:

$$CR = \frac{A}{\sqrt{P_{in}}} \qquad (6)$$

Where Pin is the mean input power of the OFDM signals More specifically, clipping method is considered as a non-linear process that causes (in & out) band distortion. In other words, the out-band causes spectral extension and can be taken away by filtering out signal after clipping. What's more, for in-band distortion causes to limit BER and disposed by performed clipping with the adequately oversampled OFDM signals (e.g., L ≥4) the BER performance will be less degraded [26]. Accordingly Figure(3) shows the impact of changing CR on a value of PAPR. It shows the CCDF compression between the OFDM original signal and the signal after reducing PAPR with clipping for different value of CR (0.1 to 1). Moreover, it demonstrates that there is a direct relation between CR and PAPR. In fact, whenever CR increases the PAPR increases too. It is clearly noticed that we can obtain a minimum PAPR can be obtained nearly 4.5dB at CR=0.3 for a typical probability 10^{-3} in comparison to original CO-OFDM system. Hence, there is a significant reduction that can be raised to achieve more 6.5dB.

V. Simulation and Results

In this section, we investigate the performance of the CO-OFDM system shown in Figure (1) at the sender, information bits is changed over into baseband OFDM signals. Meanwhile, an optical in phase/quadrature (I/Q) modulator is utilized to change the OFDM Signal into optical signal. Within this system, Matlab (2014a) has been used in order to implement both the entire OFDM sender and receptor. Likewise, VPI transmission maker Ver. 9.5 has been used in order to implement optical transmitter and receiver. Accordingly, Table (2) summarizes the required parameter to implement and simulate the system performance.

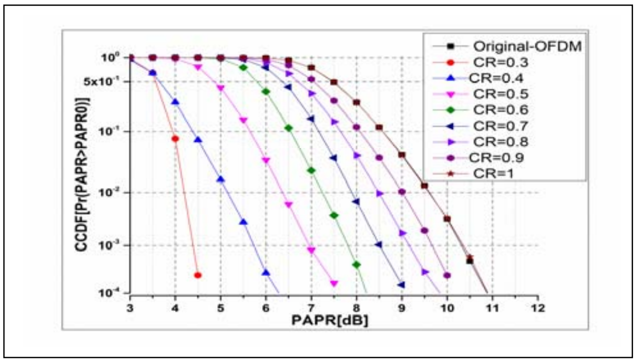


Fig .3. CCDF for Different Value of Clipping Ratio

TABLE .2. SIMULATION PARAMETERS FOR COHERENT OPTICAL OFDM

Global System Parameters	
Bit Rate	10 Gbps
Sample Rate	40 Gbps
Sequence length	8192
Samples per bit	2
QAM-4 sequence generator	
OFDM modulator	
Max possible subcarriers	128
Cyclic Prefix	1/8
Local Oscillator + CW Laser	
Carrier Frequency	193.1 THz
Power	5 dBm
Line Width	0.1 MHz
SMF+DCF	
SMF length	50 km
DCF length	5 km
Number of loop	10
Attenuation for SMF	0.2dB/km
Attenuation for DCF	0.5 dB/km
Dispersion SMF	16 ps /nm/km
Dispersion DCF	-160 ps /nm/km
Optical Amplifier EDFA	
Gain	13 dB
Noise Figure	4 dB

Importantly, to illustrate the reduction of ICI due to the phase noise of laser line width, Figure 4 shows the quality performance for system with a chosen value of CR=0.6 at a distance 55km. It has been noted that in order to estimate the ability of the proposed scheme versus the LPN by the sender and receptor laser, the line width of the laser diodes is changed from 0.1 MHz to 4 MHz. The quality factor exhibits highest level up to 10.8 dB at line width below 1MHz. In other words, as the line width increases the signal quality dramatically decreases to nearly 5.8 dB for line width 4MHz. In contrary, the quality factor (QF) achieves 10.3 dB in original system; and then an improvement of 0.5 dB is obtained in clipping scheme. Moreover, it has been found that clipping-based system is more robust against ICI caused from LPN and FNL. Additionally, there is slightly quality increase of nearly 0.2dB than the system without clipping.

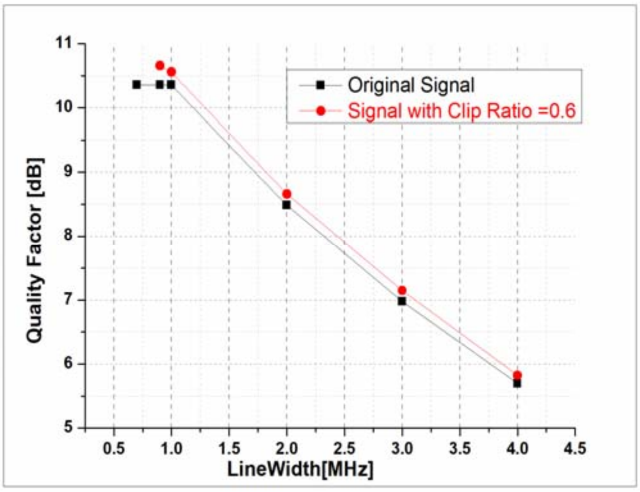


Fig .4. Quality Factor vs. Laser Line Width over 50km a single SMF

Another key result to mention is that Figure 5 explains the Error Vector Magnitude (EVM) performance comparison as a function of distance for different CR values. Furthermore, the EVM of the OFDM signal for the clipping-based system is seen to be better than the counterpart original signal. Likewise, it has been noticed that when CR becomes 0.6 is more better in the system than the clipping ratios of 0.7 and 0.8 at a distance varying from 55km to 165 km. However, it has also been illustrated that the EVM can achieve approximately the close values to each other in cases of clipping or without clipping. There is no doubt that at a long haul distance greater than 220 km the clipping-based system with a chosen CR of 0.6 becomes more robust especially once it has a better measured EVM than the others of CRs. In consequence, this result may cause an effective reduction in the nonlinear impairment of the CO-OFDM system.

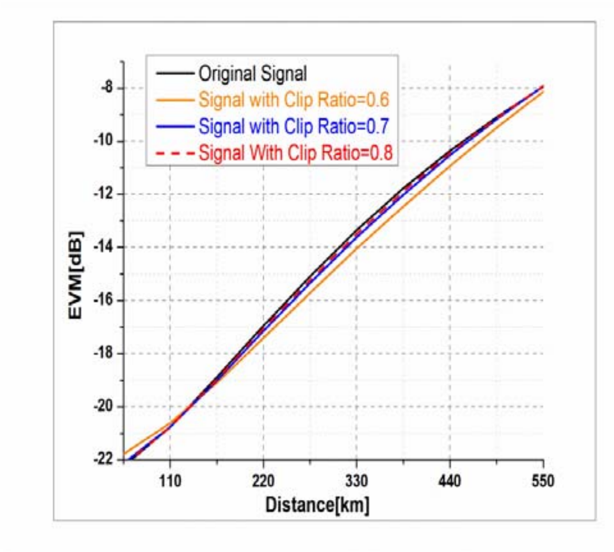


Fig .5. EVM vs. Distance for various values of clipping ratio

On the other hand, Figure.6 depicts the relationship between BER and distance in order to outline the influence of clipping on the system performance. Nevertheless, at a distance 385 km the lowest BER level for the system with clipping ratio of 0.6 can achieve $3.6\text{x}10^{-3}$ while the BER of original system with no clipping is being $2.6\text{x}10^{-2}$. Also, when clipping ratio becomes 0.7 and 0.8, BER achieve $2.79\text{x}10^{-2}$ and $2.7\text{x}10^{-2}$, respectively. Furthermore, it has been shown that once a distance increases to 550 km the BER curves will be more close to each other because of the behavior of nonlinearity process inherent in clipping algorithm. Notably, this may cause significant in-band distortion consequently and out-of -band noise that can degrade the BER of the system.

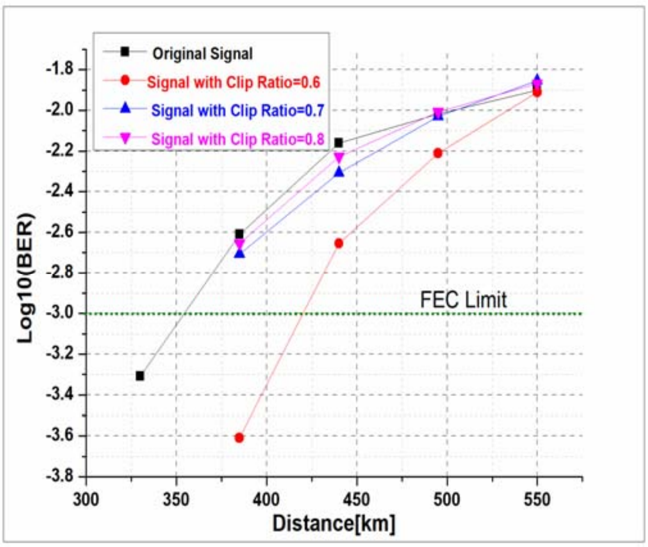


Fig .6. BER vs. Distance for various values of clipping ratio

Generally, Figure 7 shows the relations that occurs between Quality factor versus distance up to 550km in the proposed CO-OFDM system and the conventional one. It has been clearly shown that when CR changes between 0.6 and 0.8, the QF at a certain distance of 385 km can exhibit a slight change between 9.1dB and 9.3dB respectively in the system without clipping. Conversely, the QF for the proposed system increases to achieve 10.8 dB when CR is chosen to be 0.6. This means that for given CR=0.6 the CO-OFDM system has a better performance in comparison with the other values of CR. Meanwhile, once the distance becomes 550km, there is a clear decrease in QF to achieve nearly 7 dB. Moreover, the reason behind relies on the ICI reduction scheme which is based on the reduction of the effect of phase noise and the nonlinear impairment of the system using clipping algorithm.

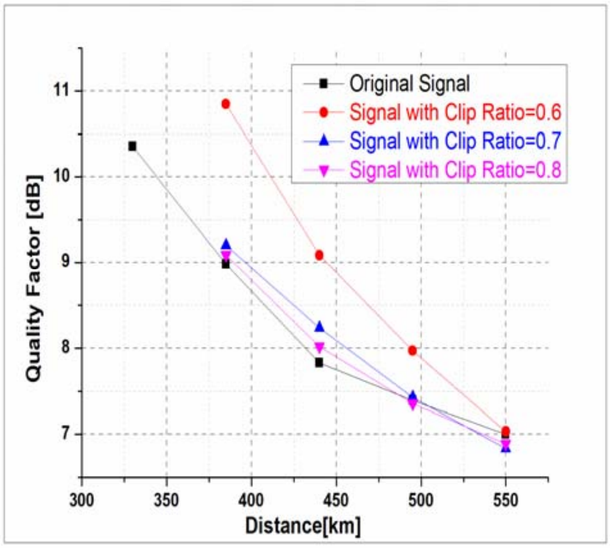
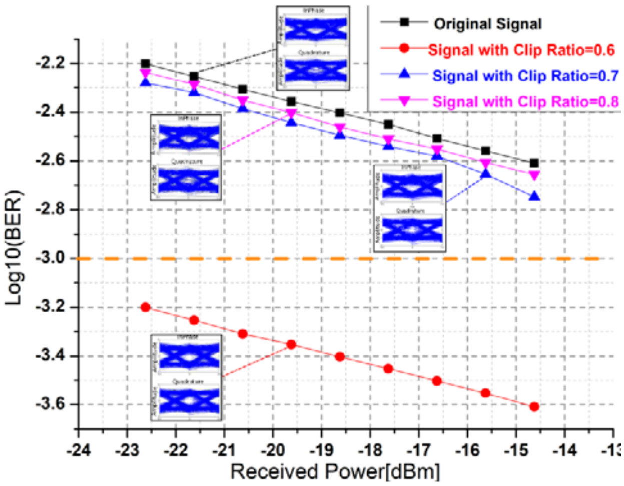


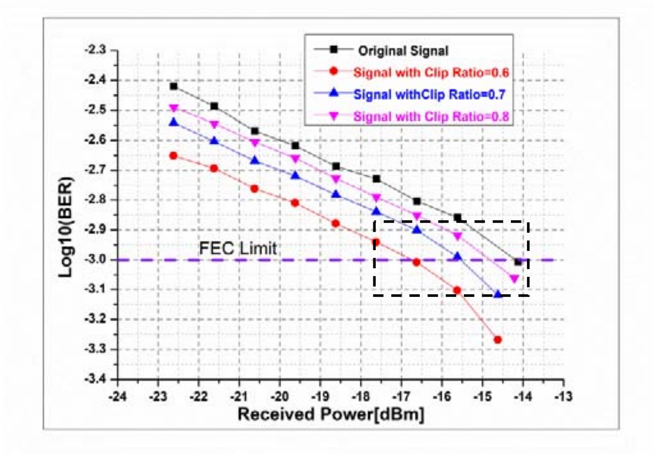
Fig .7. Quality factor vs. Distance for various values of clipping ratio

Furthermore, in order to draw the relation between the received power (RxP) and BER for the signal with and without clipping algorithm, Swept Attenuator has been used with step 1 dB. To give an illustration, Figure 8(a,b) shows the results for different clipping ratios at a distance 385km and launched laser power 5dBm and 8dBm, respectively. It is shown in figure whenever the (RxP) increases the BER decreases. However it is worth noting that a major new finding is obtained below FEC limit when CR becomes 0.6 and the received power varies between -14.5 dBm to -22.5 dBm. This would allow significant optimum improvement in receiver sensitivity and higher than other existing optical OFDM systems such IM/DD system as in[23]. Moreover, in Fig. 8a the larger size of eye opening diagram shows a lower BER effect in case of CR=0.6; and the eye smoothness also indicates less noise influence of ISI and ICI due to laser line width for 4QAM channel modulation.

However, when laser power becomes 8dBm, Fig. 8b clearly shows the improvement in the receiver sensitivity at FEC limit 10^{-3} when the received power varies from -16.5dBm to -14.1dBm. The clipping ratio of 0.6 allows the receiver sensitivity in CO-OFDM system outperforms by 1dBm and 1.7dBm compared to system at CR of 0.7 and 0.8, respectively. Meanwhile, the improvement is being about 2.4dBm compared to the original system with no clipping ratio. Hence, it has been concluded that the clipping ratio of 0.6 can achieve optimum and best performance in the receiver sensitivity and PAPR reduction.



(a)



(b)

Fig.8.The measured BER curves with different clipping ratio technique at 385km transmission distance for different launched laser power (a) 5dBm and (b) 8dBm

VI. Conclusion And Discussion

On the basis of this study, it has been noticed that the ICI cancellation using clipping algorithm has been pursued to reduce PAPR; and consequently minimizing the impact of the LPN and the fiber non-linearity as well. The present findings confirm that the proposed system based on clipping method outperforms the conventional CO-OFDM. On the other hand, the comparison performance has investigated the laser line width tolerance in the CO-OFDM system. More generally the basic finding is that the proposed clipping algorithm can be considered as ICI cancellation scheme because it has shown better phase noise tolerance in comparison `with conventional CO-OFDM. Consequently, simulation results clearly reveal the robust transmission performance with maximum allowable distance up to 550 km and good nonlinearity tolerance. Thus the proposed ICI cancellation scheme can provide better tolerance to the fiber nonlinearity and faithfully enhance the system performance in terms of QF, BER and EVM. A major new result specifies the best clipping ratio at 0.6 for a 385km transmission distance in terms of BER vs. the received power in dBm. It achieves the best and high receiver sensitivity below $1x10^{-3}$ FEC limit for 5dBm and 8dBm laser power. In addition, this would eventually reduce the resulting ICI influence of laser phase noise in combining with PAPR reduction. Importantly, from a statistical analysis the results are obtained to identify the worst case phase noise influence up to 550km in terms of Quality factor (up to 7dB) in the CO-OFDM system with and without clipping using 4QAM channel modulation. Finally, we can deduce that our suggested system can effectively lessen both the inherent ISI caused by a dispersive channel, in addition to the ICI caused by laser line width from the received signal.

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