Cyclic Prefix Reduction Technique for Direct-Detection Optical OFDM Transmission over Long-distance of SSMF

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***Abstract*- Optical Orthogonal Frequency Division Multiplexing (O-OFDM) is now used by a number of researchers because it provides major advantages in mitigating Group-Velocity Dispersion (GVD) in Single Mode Fiber (SMF). Unfortunately, when the uncompensated long-haul transmission ranges become very large, substantial dispersion is accumulated. Due to the large accumulated dispersion, the Cyclic Prefix (CP) duration will occupy a substantial fraction of the OFDM frame. This effect sets some limitations on the overall throughput and the spectral efficiency. Moreover, the transmission is inefficient because of the energy wastage contained within the CP. In the case where the Channel Impulse Response (CIR) is larger than the CP, the system performance is limited by the Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI). To reduce the CP length, a Time-domain Equalizer (TEQ) is used immediately after the channel. It can cancel the residual ISI and ICI caused by both the GVD and the CP length being shorter than the CIR.**

***Index Terms*- Optical communications, optical orthogonal frequency division multiplexing, long-haul, equalizer.**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) [1,2] is a multi-carrier modulation technology that has been proposed for fiber optic communication because of its robustness against ISI, when symbol period of each subcarrier is longer than the delay spread caused by group-velocity dispersion [3,4]. It has several advantages. The most important of them are its efficient bandwidth usage, transformation of a frequency selective fading channel into a flat fading channel and simplified channel equalization.

OFDM system adds a CP to the waveform [1,2] in which the end of the waveform block generated by the IFFT is copied and attached to the beginning of the block. The purpose of having the CP is to avoid the ISI and ICI in the received OFDM symbols. If the CP length is sufficiently long, any time shift will not affect the received signal. Therefore, the subcarriers will remain orthogonal. However, the CP wastes transmission capacity, if its length is not optimized [5]. When the CP length is longer than the CIR, ISI can be eliminated. Thus, the effect of delay spread caused by group-velocity dispersion in long-distance SMF leads to frequency selective fading of individual sub-band channels. Fortunately, this fading can easily be cancelled by one-tap Frequency-domain Equalizer [6]. However, this method will waste the energy within the CP, because the system leads to low energy efficiency. On the other hand, if the CP length is shorter than the CIR, energy wastage is reduced but the system performance will be limited by ISI and ICI [7]. ISI and ICI are a severe degradation factor for the performance of the communications system, thus they must be mitigated by equalizations.

In this paper, a TEQ, using long training OFDM symbols in the preambles, immediately after the channel and a one-tap Frequency-Domain Equalizer (FEQ) after FFT for each subcarrier are proposed in the receiver.

In order to derive the performance of the system, two types of TEQ are used, namely, Least Mean Square TEQ (LMS-TEQ) and Decision Feedback TEQ (DF-TEQ). Both TEQ are employed to show the effectiveness of reducing CP length in long-haul direct detection optical OFDM transmission. The simulation results show that, using BER of 10^{-3} as a reference, the system performance improves by 2.53 dB while considering a 4-feedforward/3-feedback-weight DF-TEQ and 1.93 dB while considering an 8-tap LMS-TEQ even though the CP length is shorter than the CIR.

This paper is organized as follows. In section 2, the system model with proposed receiver is described. In section 3, simulation results are performed to demonstrate the performance of the system. Finally, conclusions are given in section 4.

II. SYSTEM MODEL

Fig.1 shows an optical OFDM transmitter. It is composed of functional blocks for IFFT, CP, Digital to Analog conversion (D/A), Electrical-Modulation, Optical source and Optical-Modulation.

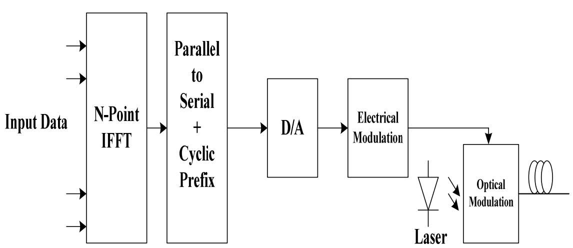

Fig.1. Block diagram of O-OFDM transmitter

If $X(p,q)$ denotes the frequency domain data symbol of the p-th sub-band of the q-th OFDM symbol, then the transmitted OFDM symbol in discrete-time domain will be shown as:

$$x(n,q) = \frac{1}{N}\sum_{p=0}^{N-1} X(p,q).\exp(j\frac{2\pi}{N}pn) \qquad (1)$$

where $x(n,q)$ is an N-point Inverse Fast Fourier Transform and n is the time domain index of the OFDM sample.

Then the CP is added to the signal to avoid the ISI and ICI provided by the long- distance SMF Channel. If $x_g(n,q)$ and g denote the extended OFDM symbol and length of the CP, respectively, it can be written as:

$$x_g(n,q) = \begin{cases} x(n-g+N,q) & 0 \le n \le g-1 \\ x(n-g,q) & g \le n \le N+g-1 \end{cases} \qquad (2)$$

After D/A conversion, the components are used to drive the electrical modulator. To provide an optical output power proportional to the electrical drive voltage, the optical modulator is assumed to be linearized. It has been shown that Mach-Zehnder modulators without linearization can be used in O-OFDM [5,8,9]. The modulator output is then coupled into the SMF channel. Receiver Gaussian Noise is then added to the channel output, so that the received samples, $y_g(n,q)$ is given by:

$$y_g(n,q) = [x_g(n,q) * h(n)] + z(n,q) \qquad (3)$$

where $h(n)$ and $z(n,q)$ are the discrete-time impulse response of the SMF Channel and Gaussian Noise in the time domain, respectively. When the CP length is shorter than the CIR, the ISI and ICI will not be completely cancelled. The residual ISI and ICI reduce the performance of the system. Transformation of Equation (3) in frequency domain can be written by:

$$Y(p,q) = H(p).X(p,q) + I(p,q) + Z(p,q) \qquad (4)$$

where $I(p,q)$ is the residual ISI and ICI due to the CP length being shorter than the CIR. To overcome this residual ISI and ICI, we propose a TEQ immediately after the channel and a 1-tap FEQ after FFT for each subcarrier. TEQ can provide multipath diversity. Furthermore, shorter CP length can reduce the energy wastage associated with the CP. Finally, the residual ISI and ICI can be cancelled by the CP and one-tap FEQ.

Fig.2 shows the proposed optical OFDM

receiver. The photodiode produces a time-domain waveform proportional to the optical power. From photodiode the waveform goes through the A/D conversion and TEQ subsequently. The proposed TEQ cancels the residual ISI and ICI. Then, CP is removed and the output will be converted to the frequency-domain using an FFT. After FFT each subcarrier is equalized by the 1-tap frequency-domain equalizer to compensate for phase and amplitude distortions due to the optical and electrical paths. The proposed receiver make a reduction in the energy wastage associated with the CP by using a shorter CP length than the CIR.

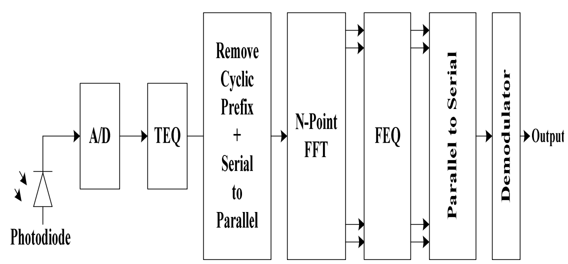

Fig.2. Block diagram of proposed O-OFDM receiver

In order to derive the performance of the system, two types of TEQ are used, namely LMS-TEQ and DF-TEQ.

A. LMS-TEQ

Fig.3 illustrates the structure of the LMS-TEQ. It is designed by complex sample-by-sample LMS operations.

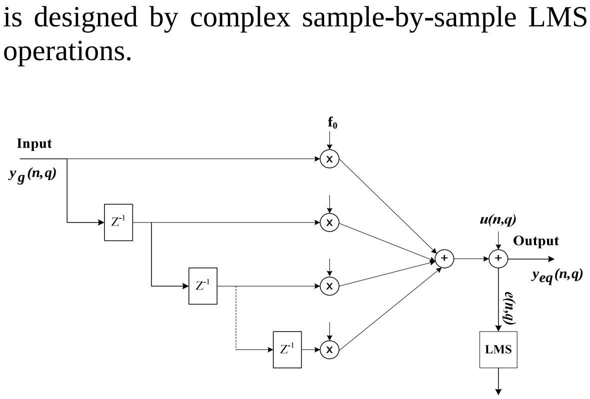

Fig.3. Structure of LMS-TEQ

It is important to know that the LMS algorithm is a linear adaptive filtering algorithm which belongs to the family of the stochastic gradient algorithms [10]. The stochastic gradient algorithms differ from the steepest descent algorithms in that the gradient is not calculated deterministically. The LMS algorithm has two parts. In the first part, the output of a transversal filter is computed according to the tap inputs and the error term is generated according to the difference between the filter output and the training data. In the second part, the adjustment of the tap weights is done according to the error term.

The LMS algorithm forms a feedback loop by the error term fed back. The filter produces an output and the difference between the output and the training data is obtained. This difference is the estimation error term. The estimation error is given to the adaptation control section. Adaptation control section multiplies the estimation error with the complex conjugate of the input taps and a step size k . The results of the corresponding taps are added to the corresponding filter taps.

Consequently, when the received samples, $y(n,q)$ is applied to the proposed receiver, the Time Domain Equalizer estimates the channel information and determines the tap weights. This adaptive process is given by:

$$f(i,n+1,q) = f(i,n,q) + k.e(n).w^*[(n-i),q)] \tag{5}$$

Where k, i, $f(i,n,q)$ and $w(n,q)$ are step size, $0 \le i \le q-1$, tap weight and received training data of the LMS-TEQ respectively. The estimated error $e(n,q)$ is given by:

$$e(n,q) = u(n,q) - y_{eq}(n,q) \tag{6}$$

where $u(n,q)$ is training data. Then, the LMS-TEQ output can be written as:

$$y_{eq} = \sum_{i=0}^{I-1} f(i,n,q).y_g[(n-i),q] \tag{7}$$

Finally, the residual ISI of $y_{eq}(n,q)$ can be canceled by the CP and one-tap Frequency Domain Equalizer.

B. DF-TEQ

Fig.4 illustrates the structure of the DF-TEQ. It is composed of feed-forward and feed-back filters. The input is passed through the feed-forward filter to remove some of the ISI from the received signal. Then, the feed-back filter estimates the residual ISI from the past decisions of the bits and subtracts it from the feed-forward filter output.

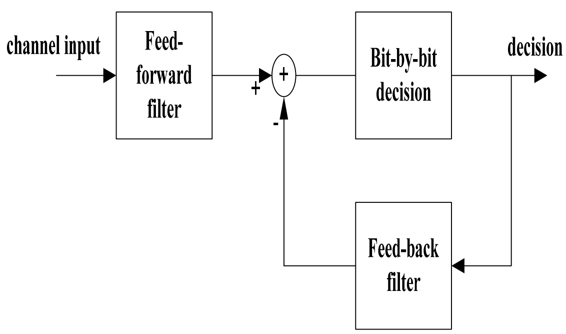

Fig.4. Structure of DF-TEQ

To decrease the noise we consider Mean Square Error (MSE) criterion. The MSE criterion can reduce the signal variance at the decision portion, so that the noise will decrease [11]. If n_1+1, n_2 and r_i are length of the feed-forward filter, length of the feed-back filter and DF-TEQ input, respectively, the DF-TEQ output can be written as:

$$A_i = \sum_{j=-n_1}^{0} f_j r_{i-j} - \sum_{j=1}^{n_2} b_j B_{i-j} \qquad (8)$$

where f_i, b_i, A_i an B_i are feed-forward filter coefficients, feed-back filter coefficients, decision device input and correct transmitted symbol, respectively.

The design of the DF-TEQ is determined by the feed-forward and feed-back filter coefficients. The feed-forward filter coefficients f_i, are given by:

$$\sum_{j=-n_1}^{0} \varphi_{kj} f_j = d_{-k}^*, \quad k = -n_1,\ldots,-1,0 \qquad (9)$$

where d_k are the CIR coefficients and φ_{kj} can be written as:

$$\varphi_{kj} = \sum_{l=0}^{-k} d_l^* d_{l+k-j} + 2N_0\delta_{kj}, k, j = -n_1,\ldots,-1,0 \qquad (10)$$

where N_0 is the variance of the noise and δ is the delta function.

By using the feed-forward coefficients from equations (9) and (10), the feed-back filter coefficients are given by:

$$b_m = \sum_{j=-n_1}^{0} f_j d_{m-j}, \quad m = 1,2,\ldots,n_2 \qquad (11)$$

III. RESULT AND DISCUSSION

A direct-detection optical OFDM with double-sideband optical signal is considered. 512 sub-carriers are modulated using a 4-QAM-constellation. The sub-carrier spacing is 40 MHz achieving a data rate of 20.48 Gb/s. It also corresponds to an OFDM symbol duration of T=25 ns. The transmission line is 32 spans of 80 km standard SMF (SSMF). The channel model is characterized by group-velocity dispersion with dispersion coefficient 17 Ps/(km-nm), wavelength 1.55 µm, fiber length 2560 km and attenuation coefficient 0.2 dB/km. The total photodiode noise is obtained by adding the contributions of shot noise and thermal noise. Both these noise are independent random processes with approximately Gaussian statistics [12].

Amplifiers with a flat gain of 30 dB and a Noise Figure (NF) of 5 dB were used after each span.
Fig.5 and Fig.6 illustrate received constellation after an 8-tap LMS-TEQ operating at optical signal to noise power ratio (OSNR)=8 dB and a 4-feedforward/3-feedback-weight DF-TEQ operating at OSNR=7 dB over 2560 km of

SSMF, respectively. The equalizers are trained before each simulation run by transmitting a known set of bits. This training approximates to a practical equalizer that would be trained by averaging over many blocks of data to reduce uncertainty. Before equalization the constellation points are spread over all phase angles because of fiber dispersion. According to Fig.5 and Fig.6, after equalization the effect of fiber dispersion and also any phase distortion due to electrical components is removed. These figures show that, by using TEQ immediately after the channel, the transmitted QAM data constellation is completely reconstructed.

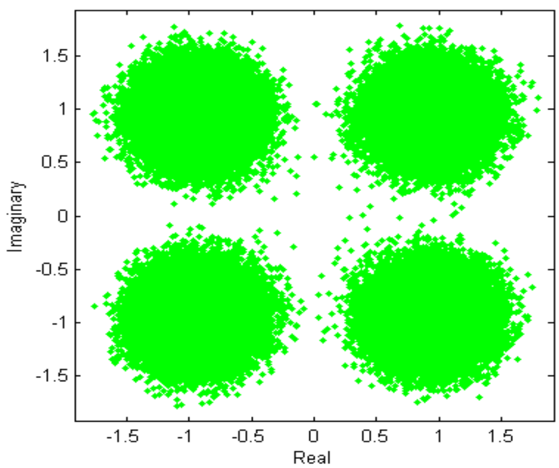

Fig.5. Received constellation after LMS-TEQ for OSNR=8 dB

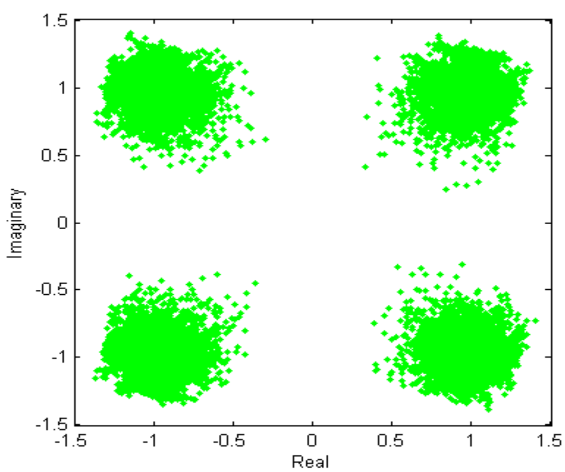

Fig.6. Received constellation after DF-TEQ for OSNR=7 dB

To plot BER versus OSNR, an OFDM symbol duration of T=25 ns is considered. The BER measured over a 12.5 GHz noise bandwidth, which is equivalent to 0.1 nm at 1550 nm. The errors were counted by comparing the transmitted and received data bits. Up to 900000 bits were used per point, enabling BER less than 10^{-5} to be estimated.

Fig.7 presents the BER in terms of OSNR for the O-OFDM receiver with and without an 8-tap LMS-TEQ for different size of CP. According to Fig.7, our results by using LMS-TEQ achieve sufficiently lower BER than the result without LMS-TEQ. Using BER of 10^{-3} as a reference, the power penalty versus CP duration for Fig.7 is plotted in Fig.8. According to Fig.8, the maximum power penalty that we have to pay is 1.93 dB if an 8-tap LMS-TEQ is not used while considering CP=T/256.

Fig.9 presents the BER in terms of OSNR for the O-OFDM receiver with and without 4-feedforward/3-feedback-weight DF-TEQ for different size of CP. According to Fig.9, our results by using DF-TEQ achieve sufficiently lower BER than the result without DF-TEQ. Using BER of 10^{-3} as a reference, the power penalty versus CP duration for Fig.9 is plotted in Fig.10. According to Fig.10, the maximum power penalty that we have to pay is 2.53 dB if a 4-feedforward/3-feedback-weight DF-TEQ is not used while considering CP=T/256.

Furthermore, the 4-feedforward/3-feedback-weight DF-TEQ achieves better performance than the 8-tap LMS-TEQ. To achieve 10^{-3} BER, LMS-TEQ requires an OSNR of 5.45 dB whereas DF-TEQ achieves the same performance at an OSNR of only 4.85 dB.

By using BER of 10^{-3} as a reference, the system performance improves by 1.93 dB and 2.53 dB while considering an 8-tap LMS-TEQ and a 4-feedforward/3-feedback-weight DF-TEQ, respectively. This improvement is due to the cancellation of residual ISI and ICI by the TEQ employing for both LMS and DF algorithm.

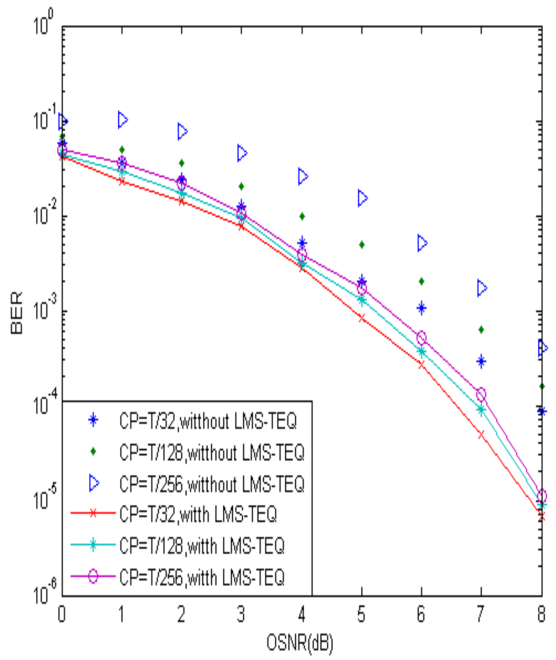

Fig.7. BER versus OSNR for O-OFDM receiver with and without an 8-tap LMS-TEQ for different size of CP

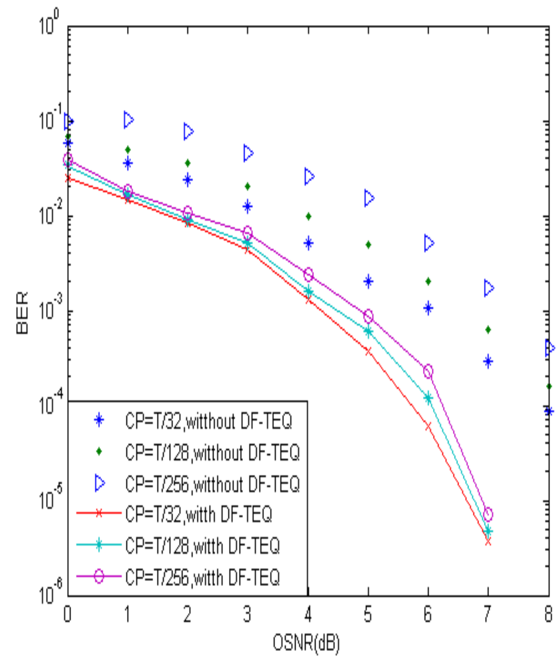

Fig.9. BER versus OSNR for O-OFDM receiver with and without a 4-feedforward/3-feedback-weight DF-TEQ for different size of CP

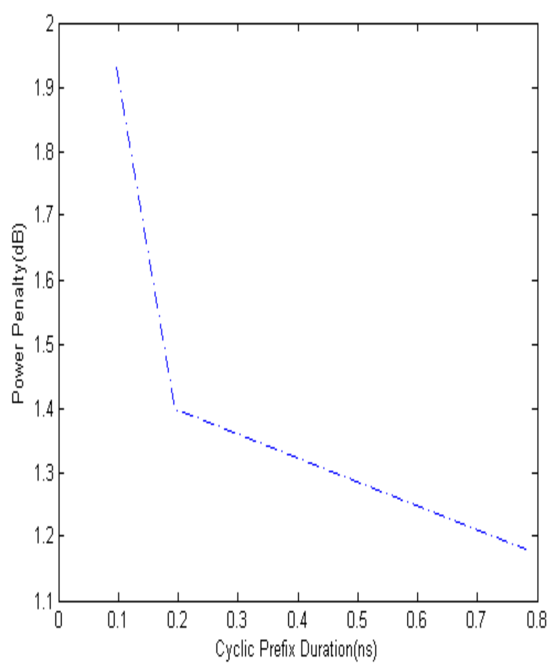

Fig.8. Power penalty versus CP duration for Fig.7 while considering BER=10^{-3} as a reference

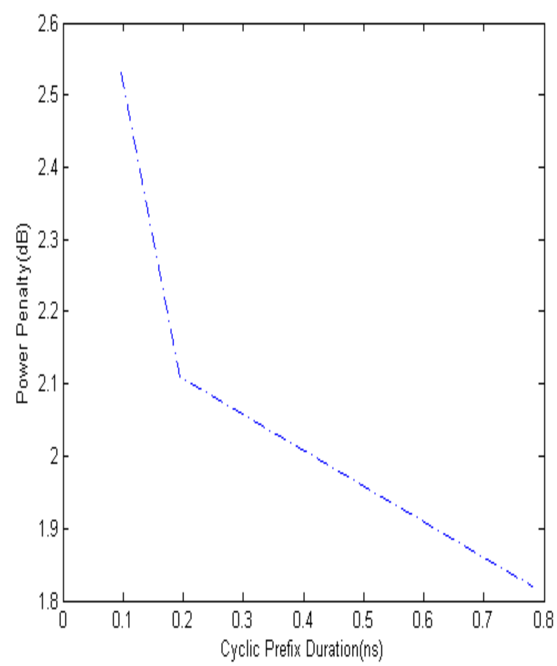

Fig.10. Power penalty versus CP duration for Fig.9 while considering BER=10^{-3} as a reference

IV. CONCLUSION

Two TEQ schemes for direct-detection O-OFDM transmission over 2560 km of SSMF are proposed to cancel the residual ISI and ICI caused by both the GVD and the CP length being shorter than the CIR. The proposed receiver is compared to the conventional O-OFDM receiver by computer simulations. From the simulation results, it is shown that the proposed receiver can achieve better BER performance than the conventional O-OFDM receiver under 2560 km of SSMF. Simulation results show a 2.53 dB improvement in the system performance while considering 4-feedforward/3-feedback-weight DF-TEQ for CP length of T/256.

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