Diversity-Combining in Asymmetrically Clipped Optical OFDM for PON IM/DD fiber link

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***Abstract*—We show taking into account realistic component parameters, the performance analysis of Diversity-combined Asymmetrically Clipped OFDM technique in intensity modulated and direct detected (IM/DD) passive optical network (PON) fiber link. The Diversity-Combined ACO-OFDM is shown to give better BER performance than conventional ACO-OFDM. Data rate of 13.2Gbps can be transmitted using 4-QAM/D-C ACO-OFDM through 60km unamplified IM/DD fiber link with split ratio of 128 users and 3dBm DFB-Laser. Throughput gain of 2.8Gbps is achieved when using the diversity-combining method. The BER performance value is fixed to 10^{-3} (limit value when Forward Error Codes are used).**

***Keywords*—IM/DD systems, PON, ACO-OFDM, BER.**

I. INTRODUCTION

Advents of novel services such as video-on-demand (VoD), real-time network games, peer-to-peer applications, Internet protocol TV (IPTV), Ultra HD TV and other emerging applications are bandwidth-hungry creating an increasing need for higher rates requests in access networks, inducing a fiber massive deployment increasingly closer to end user. Motivated by the limitations of known access network technologies [1] and empowered by the enormous bandwidth offered by optical fibers, passive optical networks (PON) are being deployed. The first next-generation PON [2] (NG-PON1) should leverage the use of existing GPON ODN to control cost. The Full Service Access Network (FSAN) defined NG-PON1 [3] as an asymmetric 10G system with rates of 10Gbps downstream and 2.5Gbps upstream with split ratio at least 64 over and a maximum reach of 60km. NG-PON1 is backwardly compatible with existing fiber installations The NG-PON2 proposal aims at rates of 40 Gb/s on existing PON-segment, taking into account the reduction of power consumption. Beyond NG-PON2 [3], different formats modulations with higher spectral efficiency compared to NRZ are planned such as: CDMA, WDM-TDM, WDM-FDM, OFDM [4]. We know that orthogonal frequency division multiplexing (OFDM) has been proposed to combat inter-symbol interference (ISI) in fiber link since time symbol can be made longer than the delay spread caused by the chromatic dispersion [4]-[5]. Low cost systems in optical communications use intensity modulated/direct detection (IM/DD). The transmitted electrical signal is modulated onto intensity of the optical carrier. Therefore, only real and non-negative signals can be transmitted [5]. In OFDM IM/DD systems, Hermitian symmetry with inverse fast Fourier transform (IFFT) is currently applied at the transmitter in order to generate a real signal. Methods known for generating non-negative OFDM signals fall into two global categories: DC-biased optical OFDM (DCO-OFDM) [4]-[5] and asymmetrically clipped optical OFDM (ACO-OFDM) [6]-[7]. In DCO-OFDM, the signal is made positive by adding a certain DC bias which increases the power requirement of the system and cannot be easily optimized for any constellation size if Quadrature Amplitude Modulation (M-QAM) is used to modulate the different OFDM carriers. Because of very high peak-to-average ratio of OFDM signals, a very high bias would be required to eliminate all negative peaks. Instead, a moderate bias is classically used and the remaining negative peaks are clipped, resulting in clipping noise in both even and odd subcarriers. A power efficient alternative to DCO-OFDM is ACO-OFDM where data is carried only on the odd subcarriers, even IFFT inputs are set to zero. The resulting bipolar signal is clipped at zero to give a non-negative signal. It is shown in [7] that with this method, all the clipping noise affects only the unused even subcarriers and not the odd ones. Since only half of the subcarriers are used to carry data, ACO-OFDM has half of the spectral efficiency of DCO-OFDM. In the literature, techniques derived from ACO-OFDM have only been studied in optical wireless communications (OWC) systems for the case of flat channel with AWGN. One of them is called: diversity-combined ACO-OFDM (D-C ACO-OFDM) which is shown to have a gain up to 3dB in electrical power [12] than the known ACO-OFDM. In this paper, we present performance analysis and results of diversity-combined ACO-OFDM in a 10Gbps IM/DD fiber link for passive optical network. In our knowledge, it is the first time that application of diversity-combined ACO-OFDM is studied for PON context with realistic components parameters. Hence, Bit Error Rate (BER) performance results are shown in terms of received optical power, optical budget, distance and data rates transmission for D-C ACO-OFDM method and compared with ACO-OFDM.

II. ACO-OFDM TECHNIQUE

The first known unipolar OFDM technique is ACO-OFDM [6]-[9]. Only the odd subcarriers carry data symbols, while the even subcarriers form a bias signal which ensures that the transmitted OFDM signal meets the non-negativity requirement. The input vector $X = [0, X_1, 0, ..., X_{N-1}]$ to the IFFT is constrained to have Hermitian symmetry as defined in (1).

$$X_k = X^*_{N-k} , \quad 0 < k < \frac{N}{2} \tag{1}$$

Prefix cyclic is appended, the resulting time domain signal x is then clipped at zero and modulates an electrical to optical converter before being sent through an optical channel. The resulting time domain signal x is real and satisfies anti-symmetry property [7] as defined below (2) :

$$x_k = -x_{k+\frac{N}{2}} \ , \quad 0 < k < \frac{N}{2} \tag{2}$$

At the receiver, the received signal is first converted from an optical signal to an electrical signal using a photodiode. The processing after this point is the same as a conventional OFDM receiver [8]. Fig. 1 presents the block diagram of an ACO-OFDM transmitter and the receiver block is shown at Fig. 2.

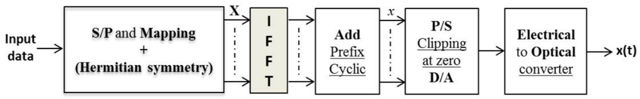

Fig. 1. Block diagram of a conventional ACO-OFDM transmitter.

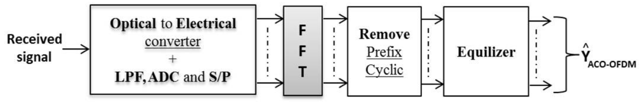

Fig. 2. Block diagram of a conventional ACO-OFDM receiver.

III. Diversity-Combined ACO-OFDM

A different approach to ACO-OFDM is diversity-combined ACO-OFDM [10]-[11] which operates on the received signal. D-C ACO-OFDM uses the same transmitter as conventional ACO-OFDM (Fig. 3). But at the receiver, both odd and even subcarriers are used after equalization as shown in Fig. 3. The signals $y'_{even,k}$ on the even subcarriers are recovered after a non-linear process of $y_{even,k}$ and combined with the signal on odd subcarriers $y_{odd,k}$ with a weighting factor α wisely chosen and given by:

$$y'_{even,k} = sgn(y_{odd,k}).y_{even,k} \tag{3}$$

$$y'_k = (1-\alpha)y_{odd,k} + \alpha.y'_{even,k} \tag{4}$$

It is shown in theory [12], for the case of OWC flat channel with AWGN that a gain of up to 3dB in electrical power can be achieved with D-C ACO-OFDM over ACO-OFDM. However, it is also shown, in the same paper, that this gain cannot be realized in a practical OWC system because of the DC-offset and low frequency noise introduced in the system.

The DC-offsets in OWC are likely present in the transmitter biasing or receiver photodiode circuit while the low frequency attenuation comes from the low pass nature of the front-ends of typical transmitters and receivers. The presence of incandescent and fluorescent lighting also introduces low frequency interference [13]. Hence, without combatting the effect due to the DC-offset, the use of non-linear operation with combining process can result in errors. New diversity combining methods are then introduced in OWC flat channel with AWGN and shown to be insensitive to the variations in the zeroth subcarrier due to the DC-offset [11]. Each of these methods makes an estimation of zeroth subcarrier at the receiver. In the first method (5), the DC value of the signal is estimated using the statistical relationship of x^2. The DC value in the second method (6) is estimated by reconstructing the even signal using the odd signal. It is shown that both techniques give better performance than conventional ACO-OFDM.

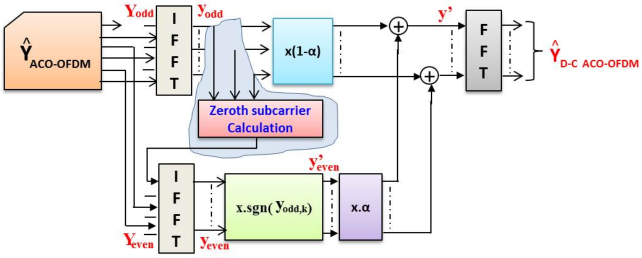

Fig. 3. Diversity-Combined ACO-OFDM receiver.

$$\hat{Y_0} = \sqrt{E\left(x^2_{ACO,k}\right)/\pi} \tag{5}$$

$$\hat{Y_0} = \sum_{k=0}^{N-1} y_{even,k} = \sum_{k=0}^{N-1} |y_{odd,k}| \tag{6}$$

IV. Description of simulated IM/DD PON link

Fig. 4 depicts the simulated 10Gbps IM/DD PON fiber link where the optical budget (optical power difference between laser output and photodiode input) can be chosen in order to evaluate if the performance is compatible with the NG-PON2 normalization [2].

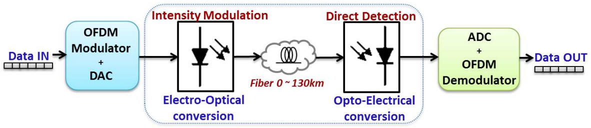

Fig. 4. Simulated IM/DD PON fiber link.

The generated OFDM signal modulates an analog 1550nm DFB-Laser of 3dBm optical power. The P(I) function of laser characteristic is plotted in Fig. 5 and presents a nonlinearity shape.

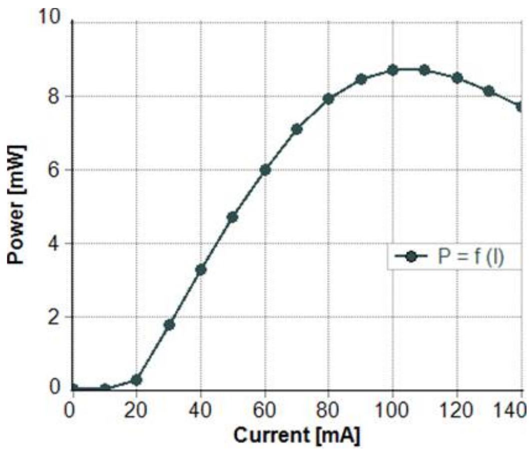

Fig. 5. Simulated P(I) laser characteristic.

To reduce the laser nonlinearity issues, normalization of the OFDM signal is made in order to operate in its linear dynamic range of radiated optical power. The emitted signal is transmitted through a standard single mode fiber (SSMF G-652) before being detected and low pass filtered at reception by a PIN photodiode with a transimpedance amplifier. Zero-Forcing equalization (ZFE) with superimposed training is used for channel estimation. Prefix cyclic of 1/32 is used with IFFT/FFT length of 512. Simulations are performed with VPI-transmissionMaker 8.7 using realistic components parameters issued from experimental measurements as set in TABLE I.

TABLE I. OPTICAL FIBER LINK

Parameters	Values
Transmission wavelength	1550 nm
Optical source	3 dBm Analog DFB-Laser
Laser rin	-150 dB
Laser bias current	30 mA
Laser threshold current	25 mA
Laser henry factor	2.5
Laser bandwidth	17 GHz, 4^{th} Bessel LPF
Laser slope efficiency	0.138 W/A
Photodetector	PIN-TIA 54 dBΩ
PIN dark current	5 nA
PIN-TIA bandwidth	20 GHz, 4^{th} Bessel LPF
Shot Noise	On
Thermal noise	20 $pA/Hz^{1/2}$
Responsivity	0.9 A/W
Fibre type	SSMF, G-652
Fiber non-linear coefficient	$2.6 \cdot 10^{-20} m^2/W$
Chromatic dispersion coefficient	17 ps/km/nm
Polarization modal dispersion coefficient (PMD)	$0.16 \mu s/km^{1/2}$
fibre loss	0.2 dB/km

The frequency response of the simulated optical link presents a chirped shape as shown and explained in [14]: when increasing the fiber length for a fixed laser henry factor value, the systems resonance frequencies will shift left and the transmission lobes will narrow. It is an appropriate example of frequency selective channel. Both OFDM modulator and demodulator blocks are implemented with MATLAB. According to M-QAM order, the bit error rate (BER) is performed [15] thanks to the EVM calculation as in (7).

$$BER = \frac{2\left(1-\frac{1}{\sqrt{M}}\right)}{log_2\left(M\right)} erfc\left(\frac{\sqrt{\frac{3}{2(M-1)}}}{EVM}\right) \qquad (7)$$

V. SIMULATION RESULTS AND DISCUSSIONS

Fig. 6 shows the BER performance of both Diversity-Combined ACO-OFDM and conventional ACO-OFDM methods for different received power after 60km transmission using 4/16-QAM modulation formats. The D-C ACO-OFDM offers significant BER improvement for all QAM modulation formats. For example of 4-QAM constellation, assuming PIN photodiode sensitivity of -23dBm that corresponds to an optical budget of 26dB (equal to split of 128 users [16] in NG-PON2 Class B+), the diversity-combining methods gives a BER gain of up to more than one decade. Otherwise, for a BER of 10^{-3} (good enough with the use of forward error codes), a gain of more than 1 dB on the received optical power is achieved compared to conventional ACO-OFDM method.

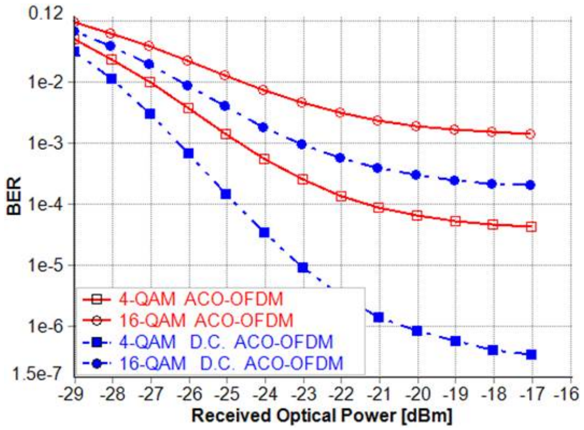

Fig. 6. BER versus received optical power after 60km transmission.

The performance enhancement of diversity-combining can be seen on Fig. 7 where the received constellation is shown to be obviously clearer than conventional ACO-OFDM after 60km.

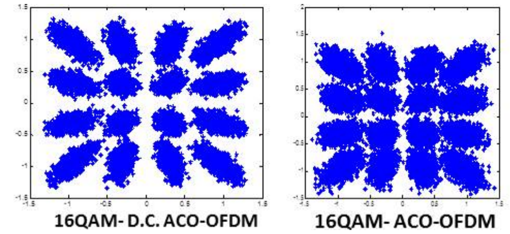

Fig. 7. Received constellations after 60km transmission distance.

Due to the noise (laser RIN, Shot noise, Thermal noise, Dark noise) and fiber nonlinearities, the equalized received constellation points in conventional ACO-OFDM are more affected than those in D-C ACO-OFDM. The BER improvement results from the fact that the non-linear process of the even subcarriers with combination of the odd subcarriers used in D-C ACO-OFDM provides good estimation for recovering data information process after the conventional ACO-OFDM equalization. Also, when 16-QAM format is used, only the diversity-combining ACO-OFDM achieves BER value of 10^{-3} after 60km. The corresponding conventional ACO-OFDM cannot.

Fig. 8 shows the BER performance in terms of the transmission distance for 26dB optical budget. It is easy to notice that the D-C ACO-OFDM can reach higher transmission distance than conventional ACO-OFDM. Thus, maximum transmission distance of 100.5km is obtained with 4-QAM ACO-OFDM at BER of 10^{-3} while more than 130km (our simulation limit) can be reached with 4-QAM D-C ACO-OFDM for 71km with 16-QAM constellation. Assuming an optical budget of 26dB, Fig. 9 shows the obtained BER performance as a function of transmission data rate for both diversity-combining and conventional ACO-OFDM schemes. So, to realize BER of 10^{-3}, the maximum data rate that can be achieved after 60km is 13.2Gbps with D-C ACO-OFDM and 10.4Gbps using conventional ACO-OFDM. This leads to a gain of 2.8Gbps when using the diversity-combining method.

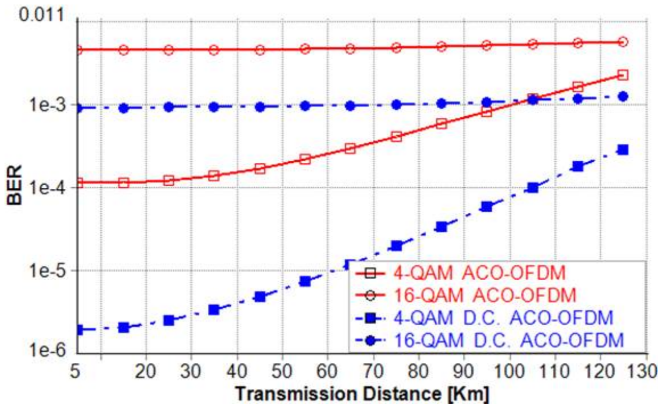

Fig. 8. BER versus transmission distance.

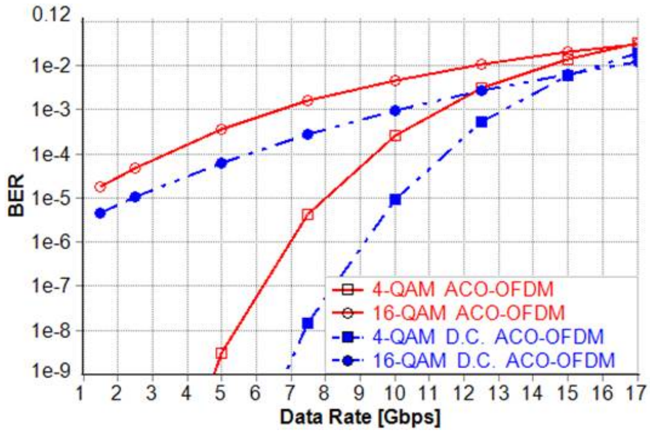

Fig. 9. BER versus transmission data rate.

VI. CONCLUSION

We analyzed and compared the performance of both diversity-combining ACO-OFDM and conventional ACO-OFDM methods for PON IM/DD fiber link using realistic components parameters. We showed that Diversity-Combined ACO-OFDM can be used for PON IM/DD fiber link, and is an interesting modulation scheme compared to conventional ACO-OFDM modulation because of its improved demodulator. It also offers significant system performance improvement in terms of distance and data rate transmission. We also showed that data rate of 13.2Gpbs with split ratio of 128 and 4-QAM constellation can be sent through 60km of SSMF link using D-C ACO-OFDM. The diversity-combining method offers throughput gain of 2.8Gbps compared with conventional ACO-OFDM technique. In the future work, impact of other components parameters will be studied and compared with DCO-OFDM.

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