

An IFFT/FFT size Efficient Improved ACO-OFDM Scheme for Next-Generation Passive Optical Network

(Invited paper)

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Abstract—In this paper, we propose for the first time, to the best of our knowledge, a novel Improved Asymmetrically Clipped Optical OFDM scheme namely, Eff-IACO-OFDM. This technique employs a novel approach to get real OFDM signals suitable for PON IM/DD systems with no use of Hermitian symmetry. It has relative low computational complexity. The system was analyzed over both an AWGN channel and realistic PON fiber link. Over an AWGN channel, it achieves up to 3 dB gain in optical power in comparison with conventional ACO-OFDM and similar performance as Noise Cancellation ACO-OFDM (NC-ACO) and Diversity-Combined ACO-OFDM (DC-ACO). It offers improvement of 20 km distance transmission with computational complexity savings of 8% compared to ACO-OFDM and similar performance as DC-ACO with very low complexity. We showed by numerical simulation that 11.3 Gb/s transmission with 32 users is possible through 50 km SSMF link by using the proposed Eff-IACO-OFDM technique. As a result, it seems to be an interesting candidate and novel modulation scheme for NG-PON cost-sensitive applications.

Keywords—Passive Optical Networks; IM/DD systems; ACO-OFDM; Computational complexity;

I. INTRODUCTION

In recent decades, the industry of communications had a fundamental impact in our daily lives and nowadays, constitutes an essential tool for information's society. Thus, the explosive growth in demand of broadband services [1] has spurred the evolution of the access network infrastructure to effectively meet the user needs in an effective way in terms of costs of both installation and maintenance. Passive optical networks (PON) are currently considered the most efficient and least costly alternative to deploy fiber to the end-user environment. Time- and wavelength-division multiplexed passive optical network (TWDM-PON) has been identified by Full Service Access Network (FSAN) as the primary solution for next-generation PON stage 2 (NG-PON2) [2]. Beyond NG-PON2, modulation formats with higher spectral efficiency than non-return-to-zero (NRZ) are preferred. OFDM-based PON has become one of the most promising solutions for future optical access and data center networks [3]-[6]. This is especially true, due to the capacity of OFDM to work with multilevel modulations, its high tolerance to chromatic dispersion, and also, its high flexibility and granularity in terms of bandwidth management [5]. In cost-sensitive optical networks context, it is generally agreed that direct-detection

optical OFDM (DDO-OFDM) is much more suitable for cost-effective deployment compared to coherent optical OFDM (CO-OFDM) [7]. Low cost systems in optical communications use intensity modulated and direct detection (IM/DD). Because the information is carried on the intensity (instantaneous power) of the emitted signal, only real and non-negative signals can be used. The general forms of OFDM techniques developed for IM/DD can be divided into two classes. The first is DC-biased optical OFDM (DCO-OFDM) in which a DC bias is added to the waveform to turn it into a positive signal. But, this method results in a high mean optical power and has the problem of residual clipping noise [6]. In the second class (main topic of this paper), the negative part of the bipolar signal is clipped at zero. Asymmetrically clipped optical OFDM (ACO-OFDM) was the first to be proposed. In ACO-OFDM, only odd frequency subcarriers are modulated before clipping so that all the clipping noise falls only on the even subcarriers [8]. Other similar schemes based- ACO-OFDM principles are proposed. One can list pulse-amplitude-modulated discrete multitoned modulation (PAM-DMT) [9], asymmetrically clipped DC biased optical OFDM (ADO-OFDM) [10], Flip-OFDM [11], Unipolar OFDM (U-OFDM) [12], both Hybrid- and Layered- ACO-OFDM methods [13]-[14], and recently, enhanced U-OFDM (EU-OFDM) [15], spectral-and-energy-efficient (SEE)OFDM [16], and Enhanced ACO-OFDM [17]. Most of these schemes can be classified into two groups: (a) First group concerns methods that can improve electrical/optical efficiency by up to 3 dB compared to ACO-OFDM [11]-[12] and the second group, (b) the modulations that can improve the spectral efficiency in comparison with ACO-OFDM [10], [13]-[17].

In ACO-OFDM, data is recovered from only the odd frequencies as the clipping noise resides only on even subcarriers. Several schemes have been proposed to improve demodulation of ACO-OFDM [18]-[24]. Using the anti-symmetry property of ACO-OFDM signal, a Noise Cancellation ACO-OFDM (NC-ACO) was developed to cancel a significant amount of noise before ACO-OFDM demodulation [22]. Without discarding the clipping noise on the even subcarriers (as in conventional ACO-OFDM), some authors showed that the residual information carried by the clipping noise can be further used to improve the demodulation performance. Then, Diversity-Combined ACO-OFDM (DC-ACO) was proposed in [19] to combine the odd subcarrier

signal with the clipping noise in a non-linear manner. Both NC-ACO and DC-ACO methods are shown to achieve up to 3 dB performance gain in AWGN flat channel [20]. When the two methods are combined, the maximum gain that can be achieved is only 3 dB. However, in practice, the use of optical transmission and the properties of both transmitter and receiver mean that the zero level of the received electrical signal may not correspond to the zero level of the emitted signal. This induces a certain limitation which degrades the system performance. To solve this issue, solutions for combatting the DC-offset were proposed in [21]-[23]. One of them has been recently developed in [24] and shown to achieve up to 3 dB gain performance as the DC-ACO scheme but with less computational complexity. We called this method “Improved ACO-OFDM (IACO)”. Computational complexity of DC-ACO scheme is relatively high, and may result in high hardware costs and/or power consumption in practice. In current field programmable gate array (FPGA)-based real-time DDO-OFDM systems, low complexity hardware implementation is generally preferred [25]. Hence, it is interesting to propose a cost-sensitive solution with fewer resources that reduces the system computational complexity. In that context, several solutions have been developed. Firstly, an IFFT/FFT size efficient method using complex operation without Hermitian symmetry (HS) was proposed and studied in asymmetrically clipped optical OFDM [26] and then applied by means of numerical simulation, for the first time, into DCO-OFDM PON fiber link communications [6]. The results show that the hardware implementation complexity and power consumption can be largely reduced with the IFFT/FFT size. Moreover, the IFFT/FFT efficient OFDM signal has similar bit error rate (BER) performance and peak-to-average power ratio (PAPR) as conventional real IFFT based DCO-OFDM. Other authors proposed a novel unipolar sign encoding technique (USE-OFDM) [27] for OFDM-based previous IFFT/FFT complex operation that increases the bandwidth efficiency by 33% and reduces computational complexity by 50% compared to conventional ACO- and U-OFDM. The latest known paper is, an experimental demonstration based fiber communications [25] where authors reduce the PAPR and improve the BER performance at the same time using a DFT-spread technique with DCO-OFDM. The results show that, with the help of PAPR reduction possible thanks to DFT-spread, more than 2-dB improvement in receiver sensitivity can be achieved after 20.62 km of SMF transmission at a BER of 3.8×10^{-3} ; and using DFT-spread, the BER performance comparison between complex IFFT-based OFDM and real IFFT-based OFDM is also performed.

In this paper, the IFFT/FFT size efficient method based-Improved ACO-OFDM (Eff-IACO-OFDM) is developed and proposed for PON IM/DD fiber link. The transmission performance of such proposed optical OFDM signal is investigated by means of numerical simulation in terms of received optical power (ROP) and distance transmission. Optical split ratio loss is taken into account to consider the number of users [optical network units] who can share the same physical medium (the feeder). To the best of authors, this is the first time that the proposed method is presented with further discussion in terms of computational complexity for a realistic chirped optical channel model as illustrated on Fig.1 in [6]. Simulations are performed thanks to VPI Systems[®], taking into account realistic optoelectronic device models issued from experimental characterizations of the French ANR EPOD project to which we contributed.

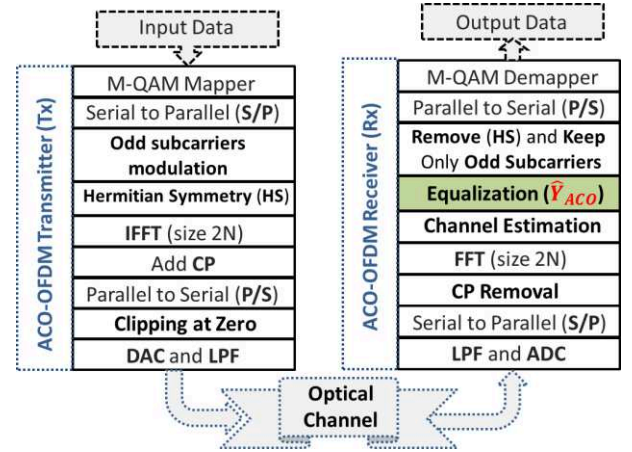


Fig. 1: Block diagram of Conventional ACO-OFDM.

II. CONVENTIONAL OFDM SYSTEMS

A. Conventional ACO-OFDM system model

In ACO-OFDM scheme (Fig. 1), only the odd subcarriers carry data symbols, while the even subcarriers form a bias signal which ensures that the transmitted signal meets the non-negativity requirement of the optical channel [8]. The IFFT input vector $X = [0, X_1, 0, X_2, 0, \dots, X_{2N-1}]$ if we consider an IFFT size of $2N$ is constrained to have Hermitian Symmetry (HS) as defined in (1). This means that only $N/2$ of the $2N$ complex inputs are independent. The resulting time domain signal x at the IFFT output is real and satisfies anti-symmetry property defined by (2).

$$X_k = X_{2N-k}^*, \quad 0 < k < N \quad (1)$$

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

Cyclic prefix (CP) is appended; the resulting time domain signal is then clipped at zero and sent through the optical channel after digital-to-analog-converter (DAC). At the receiver, the signal is converted back to the digital domain via an analog-to-digital-converter (ADC). Then CP is removed and data symbols are recovered onto only the odd subcarriers after FFT operation, channel estimation, equalization and HS removal.

B. Conventional Noise Cancellation ACO-OFDM system

Noise Cancellation ACO-OFDM (NC-ACO), is a first scheme derived from ACO-OFDM [18]. Its transmitter is identical to a conventional ACO-OFDM transmitter. The only difference with conventional ACO-OFDM is the noise cancellation processing performed at the receiver, where the anti-symmetry (2) of the time samples of ACO-OFDM is used to identify, which samples of the received signal are most likely to be due to the addition of noise. These identified samples are then made zero. Fig. 2(a) shows the block diagram of a conventional Noise Cancellation ACO-OFDM scheme. After the noise cancellation process, the rest of the method is similar to conventional ACO-OFDM, previously reminded. The mathematical details about the noise cancellation process is further described in [20] for a flat AWGN channel and performance results can be found in [22] for realistic IM/DD fiber link channel. With this method, it is shown that a performance gain of up to 3 dB in optical power can be achieved over an AWGN flat channel, due to the removal of half of the noise samples. However, as shown in [22] for IM/DD fiber link, there is no additional gain compared to

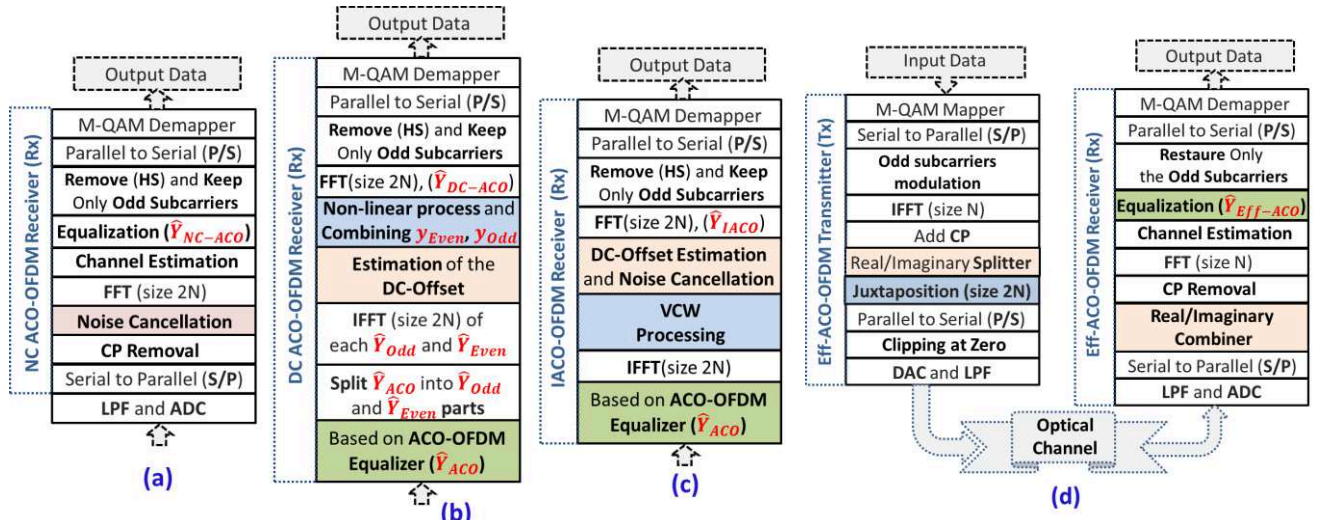


Fig. 2: Block diagram of: (a) Conventional NC-ACO receiver, (b) Conventional DC-ACO receiver, (c) Conventional IACO receiver and (d) the IFFT/FFT size efficient ACO-OFDM scheme (Eff-ACO).

conventional ACO-OFDM, due to the selective frequency behavior of the optical channel.

C. Conventional Diversity-Combined ACO-OFDM system

A different approach to ACO-OFDM is called “Diversity-Combined ACO-OFDM (DC-ACO)” [20]-[23]. DC-ACO uses the same transmitter as conventional ACO-OFDM. But at the receiver side, instead of recovering the data using the equalized symbol vector $\hat{Y}_{ACO}$, this vector is further processed to recover the information carried on the even subcarriers. As shown in Fig. 2(b), $\hat{Y}_{ACO}$ is split into vectors of odd and even subcarriers, $\hat{Y}_{Odd}$ and $\hat{Y}_{Even}$. Then, $\hat{Y}_{Odd}$ is input to an IFFT block and its output y_{Odd} is used to provide the estimation of the DC-Offset, $\hat{Y}(0)$ given by [23] as:

$$\hat{Y}(0) = \sum_{k=0}^{2N-1} |y_{Odd}(k)| \quad (3)$$

By non-linear and combining process, the $\hat{Y}_{Even}$ component with the zeroth subcarrier substituted with $\hat{Y}(0)$ is input to another IFFT block resulting to output signal y_{Even} . The absolute value of y_{Even} is then multiplied by the sign of y_{Odd} in order to recreate a bipolar signal y'_{Even} . The combined signal y' is finally obtained using (4) where α is a weighting factor [22]. A final FFT is then performed to give $\hat{Y}_{DC-ACO}$ from which the data is recovered as in conventional ACO-OFDM system.

$$y' = (1 - \alpha)y_{Odd} + \alpha y'_{Even} \quad (4)$$

It is shown in theory [21], for the case of optical wireless (OWC) flat channel with AWGN that a gain performance of up to 3 dB in electrical power can be achieved with DC-ACO over ACO-OFDM. It was also assumed that combining noise cancellation with diversity-combined ACO-OFDM can result in a gain of more than 3 dB. However, when the two systems are combined, the maximum gain that can be achieved is only 3 dB [22].

D. Conventional IACO-OFDM system model

As the complexity processing of DC-ACO is relatively high, it may result in practice, in high hardware costs and/or power consumption. The improved ACO-OFDM (IACO) is proposed in presence of DC-Offset [24] in order to achieve at least, the same demodulation performance as DC-ACO but

with less computational complexity. The idea of IACO technique is based on the noise cancellation algorithm, but after conventional ACO-OFDM equalization. To integrate the estimation of the DC-Offset, the IACO algorithm uses a novel concept of virtual clean window (VCW) of the ACO-OFDM signal. Due to the clipping in the transmitter, ideal ACO-OFDM signal is composed of many zeros. At the receiver side, these zeros form a virtual window, which is “clean” for observation of impairments and noise, without interference from data signal. To understand more the VCW principle, we can find that all the non-zero amplitudes in the VCW are reset to zeros in noise cancellation algorithm. If there is no DC-Offset, the NC-ACO demodulation performance can be apparently improved as a large of amount of noise has been canceled. But, in the presence of DC-Offset, the demodulation performance will be degraded, as it cannot be canceled by the zero-clipping. To address this issue, a VCW is explored to deal with both DC-Offset and noise simultaneously. As shown in Fig. 2(c), after equalization in conventional ACO-OFDM, the equalized symbols are then input to an IFFT block resulting to a time domain signal $\hat{y}_{ACO}$ expressed as follows:

$$\begin{aligned} \hat{y}_{ACO}(n) &= \sum_{k=0}^{2N-1} \hat{Y}_{ACO}(k) e^{\frac{j2\pi kn}{2N}} \\ &= x_{ACO} + d_0 + w_0(n) \end{aligned} \quad (5)$$

Where $(2N)$ is the IFFT size, x_{ACO} the emitted ACO-OFDM signal, d_0 and $w_0(n)$ represent respectively the DC-Offset and noise after equalization. Then, a VCW processing with DC-Offset is done. According to the anti-symmetry property (2) and zero-clipping operation, the identification of the VCW in the presence of DC-Offset can be simplified to a series of pairwise detection between two hypotheses [18], $H_0: \hat{y}_{ACO}(n) > 0, \hat{y}_{ACO}(n+N) = 0$ or $H_1: \hat{y}_{ACO}(n) = 0, \hat{y}_{ACO}(n+N) > 0$ for $n = 0, 1, \dots, N-1$. Based on these established hypotheses, the decision criterion will be:

$$\begin{aligned} &H_0 \\ \hat{y}_{ACO}(n) - d_0 &\geq \hat{y}_{ACO}(n+N) - d_0 \\ &H_1 \end{aligned} \quad (6)$$

Thus, based on (6), the VCW can be expressed as a set of index $I \triangleq \{n_i, \text{ for } i = 0, 1, \dots, N-1\}$ where

$$n_i = \begin{cases} i + N & \text{if } H_0 \text{ is true} \\ i & \text{if } H_1 \text{ is true} \end{cases} \quad (7)$$

Given the identified VCW, the estimation of the DC-Offset can be obtained as follows:

$$\hat{d} = \frac{1}{N} \sum_{i=0}^{N-1} \hat{y}_{ACO}(n_i) = d_0 + e(n) \quad (8)$$

Where $e(n)$ is the estimation error whose power is as large as $4/N^2$ of that of $w_0(n)$. With sufficiently large N value, the estimation error $e(n)$ becomes so small that we can approximatively take $\hat{d}$ as the real DC-Offset. When getting the DC-Offset value, it is possible to cancel it with the noise on $\hat{y}_{ACO}(n)$ by (9)-(10):

$$y_1(n) = \begin{cases} \hat{y}_{ACO}(n) - \hat{d} & \text{if } n \in \bar{I} \\ 0 & \text{if } n \in I \end{cases} \quad (9)$$

$$y_2(k) = \begin{cases} y_1(k) & \text{if } y_1(k) \geq 0 \\ 0 & \text{if } y_1(k) < 0 \end{cases} \quad (10)$$

Finally, we can simply restore the data directly from the odd subcarriers of $y_2(k)$, $k = 0, 1, \dots, 2N - 1$. As results, over AWGN flat channel, it is shown in [24], that IACO-OFDM performs the same performance as DC-ACO with low complexity (see TABLE 1 of the paper).

The IACO technique reduces the computation complexity of DC-ACO by just one IFFT block but has twice the conventional ACO-OFDM complexity. In order to reduce the computational complexity of IACO scheme, we introduce a new approach from [6] and [26] that offers similar BER and PAPR performances while reducing hardware implementation complexity and power consumption with reduced IFFT/FFT size.

E. An IFFT/FFT Efficient size IACO-OFDM system model

Before describing our proposed scheme Eff-IACO-OFDM (Eff-IACO), let us introduce the use of the new approach based ACO-OFDM scheme. This developed approach has been first proposed by [26] and further described by [6] and [25]. The only difference compared with conventional ACO-OFDM is the use of half IFFT/FFT sizes with no Hermitian Symmetry. In the transmitter, $N/2$ data symbols are directly input into the odd subcarriers of an IFFT block without being constrained to have HS property. Then the resulting complex output with CP is split into two signals: real and imaginary parts that are juxtaposed in time domain and clipped at zero as shown in Fig. 2(d). Then, the signal is sent through the channel after digital-to-analog conversion. As the length of the OFDM frame is doubled while the IFFT/FFT size is reduced by half, the spectral efficiency of the Eff-ACO-OFDM (Eff-ACO) is identical to the conventional ACO-OFDM. At the receiver side, after accurate symbol synchronization [25], [28], the signal is converted back to a complex signal [25] and the next steps are similar to conventional ACO-OFDM ones.

In our proposed scheme (Eff-IACO), we combine the use of the new approach with the presented IACO technique (See section II.D). In Eff-IACO-OFDM, the transmitter is the same as the Eff-ACO-OFDM, but the receiver is different and presented in Fig. 3(a). After proper Eff-ACO-OFDM equalization, the signal is converted back to time domain by an IFFT transform. Then, the complex output is split again into two components (real and imaginary parts). VCW in

presence of DCO-Offset and noise cancellation (6)-(10) are processed, followed by zero-clipping. Thus, an FFT transform is applied after real/imaginary combiner to give a new complex symbols for information data recovery.

F. PAPR and Computational Complexity

Based our previous work [6] and the results from [25]-[26], it is clear that PAPRs of all presented schemes are similar. PAPR is one of the important disadvantages of OFDM modulation. It is defined as the ratio of the maximum peak power to the average power over each OFDM symbol, for example (11) with signal x_{ACO} , where $n = 0, 1, \dots, 2N - 1$:

$$PAPR(x_{ACO}) = \frac{\max\{|x_{ACO}(n)|^2\}}{E\{|x_{ACO}(n)|^2\}} \quad (11)$$

The computational complexity is defined as the number of multiplications and additions (operations) in transmitter and receiver blocks. For an IFFT/FFT block size of N' , it requires approximately $4 \cdot (N') \log(N')$ real operations [6]. Assuming that N' is equal to $2N$ (in conventional schemes) and N (in the new approach), the total computational complexity of both presented schemes is summarized in TABLE 1.

TABLE 1: Computational Complexity of presented Unipolar OFDM Schemes

OFDM schemes	Number of IFFT block in transmitter	Number of IFFT and FFT blocks in receiver	Total computational complexity
ACO	1	(0 x IFFT) + (1 x FFT)	A= $(16N) \log(2N)$
Eff-ACO	1	(0 x IFFT) + (1 x FFT)	B1= $(8N) \log(N)$
NC-ACO	1	(0 x IFFT) + (1 x FFT)	B2= $(16N) \log(2N)$
DC-ACO	1	(2 x IFFT) + (2 x FFT)	B3= $(40N) \log(2N)$
IACO	1	(1 x IFFT) + (2 x FFT)	B4= $(32N) \log(2N)$
Eff-IACO	1	(1 x IFFT) + (2 x FFT)	B5= $(16N) \log(N)$

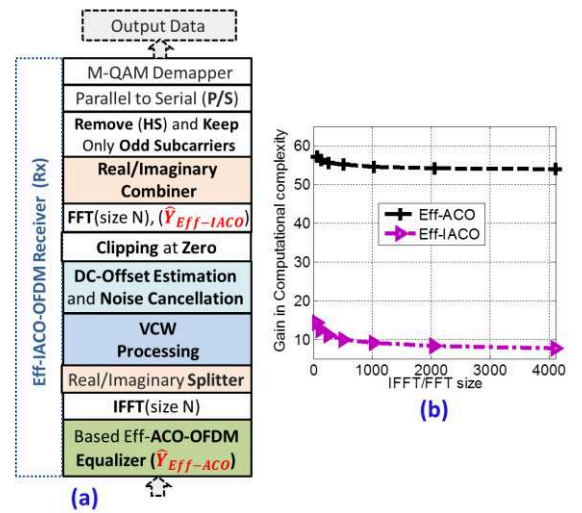


Fig. 3: (a) Receiver block diagram of proposed Eff-IACO-OFDM, (b) Computational complexity gain in comparison with ACO-OFDM versus IFFT/FFT size.

It can be seen that improvement in processing complexity is mainly reached by reducing the number of required IFFT and FFT. Then, DC-ACO and IACO are the most computation intensive processing in demodulation. By using the ratio $(B_i/A, i = \{1, 2, \dots, 5\})$ as the computational complexity

gain compared to ACO-OFDM, we can see in Fig. 3(b) that gain of respectively 54% and 8% can be reached using respectively the (Eff-ACO) and (Eff-IACO) OFDM schemes.

III. SIMULATIONS RESULTS AND ANALYSIS

In this section, we present results obtained via simulations over a flat additive white Gaussian noise (AWGN) and over realistic optical fiber link. Each OFDM symbol is generated as follows: IFFT/FFT size of $2N=512$, 4/16 QAM mapping and 32 samples are used as CP. The first OFDM symbol is used for time synchronization; the next 29 symbols serve to estimate the channel response by zero-forcing and 270 OFDM symbols are used to infer transmission performances. The digital OFDM signal is generated using Matlab[®]. Simulated IM/DD PON link (See Fig. 7 of paper [6]), is conducted by co-simulation between VPISystems[®] and Matlab[®] with realistic optical channel parameters. A real-valued baseband OFDM signal is used to modulate a 1550 nm analog DFB laser (1915 LMA). The same optical channel parameters of paper [6] are used. The simulated laser bandwidth is 7.5 GHz at bias current of 30 mA. The emitted power is 7 dBm and the receiver (a PIN diode with its transimpedance amplifier) has 12 GHz 3dB-bandwidth. The generated OFDM signal is sent to a DAC of 12 GS/s with 10 bits vertical resolution. This configuration allows a bit rate of respectively 5.65 Gb/s with 4QAM and 11.3 Gb/s with 16QAM modulations when ignoring preamble symbols. A Variable Optical Attenuator is used to emulate the power budget and to change the received optical power (ROP). A Standard G.652 Single Mode Fibre (SSMF) is considered in the simulation and BER performance is evaluated as follows [29]:

$$BER = 4 \left(1 - \frac{1}{2 \left[2^{\frac{\log_2(M)}{2}} - 1 \right]} \right) Q \left(\sqrt{\frac{2 \cdot SNR}{n_c^2}} \right) \quad (12)$$

Where SNR is the measured signal-to-noise-ratio, n_c the constellation normalization factor that can be found in [6] and Q , the Q-function defined by: $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2/2} du$.

A. Performance over a flat AWGN channel

In the literature, for OWC AWGN channel, the optical average power of the transmitted signal is generally fixed to unity. In order to study the optical power efficiency, the normalized optical energy-per-bit to noise power is considered. Results obtained with all presented schemes are shown in Fig. 4. It can be seen in Fig. 4(a) that both NC-ACO- and DC-ACO-OFDM outperforms the conventional ACO-OFDM as expected and a gain of up to 3dB in optical power can be achieved. Also, we find that when noise cancellation and diversity-combined are used together, no additional performance gain is obtained. This is because the output signal from the NC-ACO has identical values on its odd and even components which results in no gain when diversity combining is then applied. In Fig. 4(b), we can see that the improved ACO-OFDM also achieves the same performance as DC-ACO with advantage of less computational complexity. The results of Fig. 4(c) show that the use of an IFFT/FFT efficient size scheme can also reach the same BER performance when considering the associated conventional ACO- or IACO-OFDM scheme. As an example, the Eff-ACO- and respectively the Eff-IACO- OFDM reach similar BER values as respectively ACO- and IACO-OFDM. Another result is that both the Eff-IACO- and IACO-OFDM method outperform the ACO- method by 3dB in terms of $E_b(\text{opt})/N_0$.

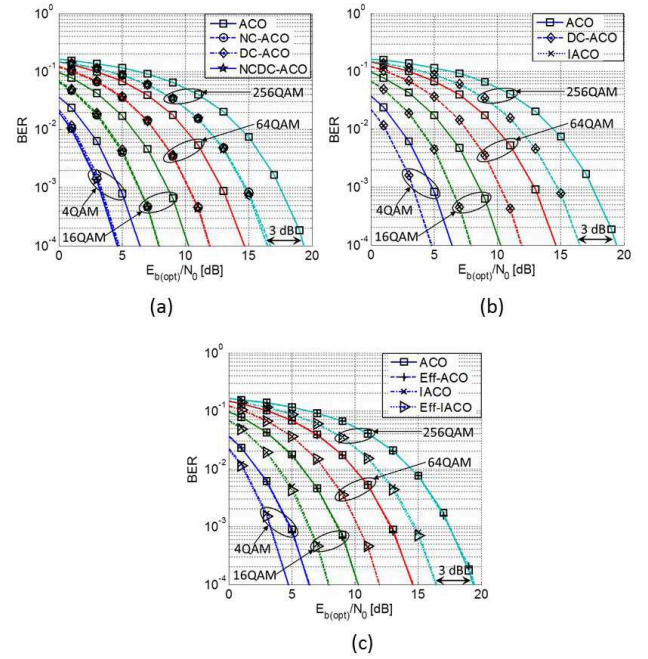


Fig. 4: BER versus $E_b(\text{opt})/N_0$ performance in flat AWGN channel for: (a) ACO-, NC-ACO, DC-ACO and NCDC-ACO techniques, (b) ACO-, DC-ACO- and IACO- techniques, (c) ACO-, Eff-ACO, IACO and Eff-IACO techniques.

In the rest of the paper, we investigate the system performance of the proposed Eff-IACO-OFDM over a realistic PON fiber link.

B. Performance over a realistic PON fiber link

Fig. 5 presents the BER performance obtained for the case of realistic PON fiber link.

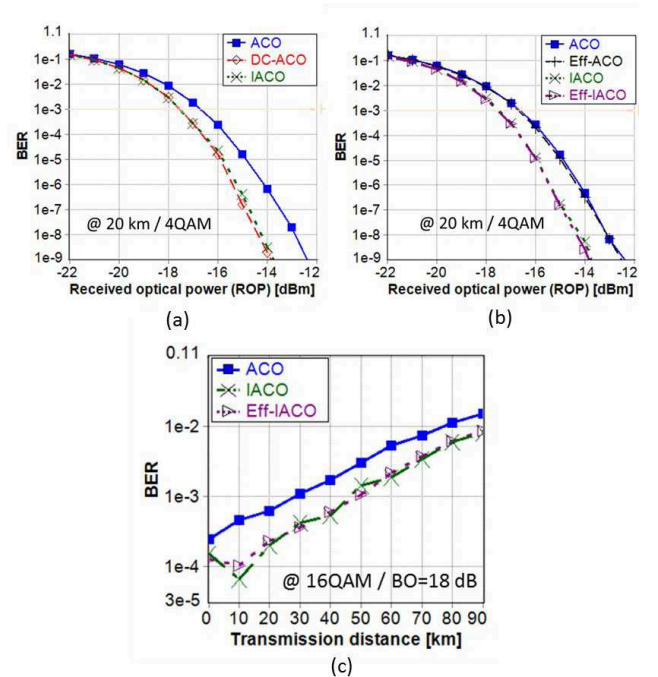


Fig. 5: BER versus - (a) received optical power (ROP) after 20 km with 4QAM for ACO-, DC-ACO- and IACO- techniques, (b) received optical power (ROP) after 20 km with 4QAM for ACO-, Eff-ACO-, IACO- and Eff-IACO- techniques, (c) transmission distance at 11.3 Gb/s with power budget of 18dB.

It can be seen in Fig. 5(a), that both the DC-ACO and IACO- OFDM techniques give almost the similar BER performance in terms of the received optical power (ROP). For example, at BER value of 10^{-9} , they reach a gain of almost 1.7 dB compared to conventional ACO-OFDM. With ROP value of -14 dBm, a gain of 3 decades in terms of BER can be reached compared to ACO-OFDM method. This improvement of the two methods is due to their robustness against the channel limitations like the induced DC-Offset and frequency selectivity of the IM/DD channel. Although the frequency selectivity of the IM/DD optical channel, we show in Fig. 5(b) that the Eff-ACO respectively the Eff-IACO methods don't degrade the system performance achieved by ACO respectively IACO-OFDM techniques. According to Fig. 5(c), we show that the proposed Eff-IACO-OFDM outperforms the conventional ACO-OFDM in terms of distance transmission with quasi-similar performance with its corresponding conventional scheme (IACO-OFDM). For example, to satisfy a BER of 10^{-3} (with the use of FEC: Forward Error Correction) at data rate of 11.3 Gb/s, 50 km distance can be reached using both IACO and Eff-IACO compared to 30 km distance reached with conventional ACO-OFDM for power budget value of 18 dB (optical split of 32 users in NG-PON context). This leads to an additional distance of 20 km using the Eff-IACO-OFDM scheme.

IV. CONCLUSION

The Eff-IACO-OFDM system presented in the paper seems to be very interesting scheme and novel. Low-cost PONs employing IM/DD would benefit from this solution. It is based on our previous work [6]. The system was analyzed over both an AWGN channel and realistic NG-PON fiber link. Gain of 3 dB in optical power in comparison with conventional ACO-OFDM was achieved over an AWGN flat channel for similar performance as both NC-ACO- and DC-ACO- OFDM. The proposed technique is shown to offer improvement of 20 km distance transmission with computational complexity savings of 8% compared to ACO-OFDM without any kind of dispersion compensation modules.

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