Performance analysis of known unipolar optical OFDM techniques in PON IM/DD fiber link

M. F. Sanya, L. Djogbe, A. Vianou, and C. Aupetit-Berthelemot

***Abstract*—We show taking into account realistic component parameters, the performance analysis of known power efficient unipolar optical OFDM techniques in a 10Gbps intensity modulated, direct detected (IM/DD) fiber link for passive optical network (PON) application. The Diversity-Combined ACO-OFDM is shown to give better BER performance in overall studied case and to be suitable to efficiently compensate frequency selective distortion of optical fiber link channel. We also show that data rate of 10Gpbs with split ratio of 128 and 4-QAM modulation format can be sent through 60km of SSMF fiber using Noise cancellation ACO-OFDM and 109km using Diversity-Combined ACO-OFDM. The BER performance value is fixed to 10^{-3} (limit value when Forward Error Codes are used).**

***Index Terms*— Unipolar optical OFDM techniques, IM/DD, PON.**

I. INTRODUCTION

ADVENTS of novel services like Video-on-Demand (VoD), real-time network games, peer-to-peer applications, Internet Protocol TV (IPTV) and other emerging applications are creating an increasing need for high rates requests or high end users bandwidths. 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 (Optical Distribution Network) to control cost. The Full Service Access Network (FSAN) has defined NG-PON1 [3] as an asymmetric 10G system with rates of 10Gbps downstream and 2.5Gbps upstream and a split ratio at least 64 over at least the maximum transmission reach of 60km. NG-PON1 is backwardly compatible with existing fiber installations and tries to facilitate high bandwidth provision, large split ratio and extended network reach. According to FSAN, data rate of 40Gbps per wavelength over at least 60km are expected in the second phase. In NG-PON2 [3], different modulation formats with higher spectral efficiency than NRZ are planned such as: CDMA, WDM and multi-carriers modulations (like OFDM) [3]. 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 modal dispersion [4]-[5]. Many systems in optical communications use intensity modulated/direct detection (IM/DD) because it is less expensive. In (IM/DD) systems, the transmitted electrical signal is modulated onto intensity of the optical carrier. Therefore, only real and non-negative signals can be used [5]. To generate real signals at the transmitter in IM/DD OFDM system, it is possible to use an inverse fast Fourier transform (IFFT) which input is constrained to have Hermitian symmetry at the expense of half of the spectral efficiency. Methods known for generating non-negative OFDM signals for IM/DD applications fall into two global categories: DC biased optical OFDM (DCO-OFDM) [3], [5] and asymmetrically clipped optical OFDM (ACO-OFDM) [6], [7]. In DCO-OFDM, the signal is made positive by adding a 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 normally used and the remaining negative peaks are clipped, resulting in clipping noise in both even and odd subcarriers. An optical power efficient alternative to DCO-OFDM is ACO-OFDM [7]. In the literature, some of unipolar techniques with optical power efficiency exist in wireless communications and derive from DCO- or ACO-OFDM. We name: Noise cancellation ACO-OFDM (N.C. ACO-OFDM) [8], Diversity-combined ACO-OFDM (D.C. ACO-OFDM) [9], [11] and Unipolar OFDM (U-OFDM) [10]. In this paper, we provide analysis and comparison performance of these known unipolar techniques for the context of PON optical fiber link. In our knowledge, it is the first time that some results are presented taking into account realistic component models and parameters issued from experimental characterization. The rest of this paper is organized as follows: we provide an overview of known power efficient unipolar optical OFDM techniques in next section. Description of simulated PON IM/DD fiber link scheme is present in Section III. The Bit Error Rate (BER) performance is presented for the case of flat Additive White Gaussian Noise (AWGN) channel and for a real PON fiber link channel. Simulation results and discussions are given in Section III before we draw conclusions.

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M. F. Sanya from LETIA, EPAC,UAC in Benin is with XLIM Laboratory, University of Limoges, 87068 Limoges, France (e-mail: frejus.sanya@ensil.unilim.fr).

C. Aupetit-Berthelemot is with XLIM UMR-CNRS 7252, University of Limoges, 16 rue Atlantis 87068 Limoges, France (e-mail: christelle.aupetit@ensil.unilim.fr).

L. Djogbe and A. Vianou are with LETIA Laboratory at Polytechnic School of Abomey-Calavi University in BENIN, 01 B.P. 2009, Cotonou-BENIN (e-mail : leopold.djogbe@epac.uac.bj, avianou@yahoo.fr, letia.uac.bj).

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II. POWER EFFICIENT UNIPOLAR O-OFDM TECHNIQUES

The first known unipolar OFDM technique is ACO-OFDM [6] where data are carried only on the odd subcarriers. Data are mapped only to the odd IFFT inputs and all the even inputs are set to zero. The resulting bipolar signal at the output of the IFFT is clipped at zero to give a non-negative signal. It is shown in [7] that all the clipping noise affects only the unused even subcarriers, but not the odd ones. Such as only half of the subcarriers are used to carry data, ACO-OFDM has half of the spectral efficiency of DCO-OFDM. Fig. 1 presents the block diagram of an ACO-OFDM transmitter; the receiver block is shown at Fig. 2(a).

In this section, we give a brief summary of three unipolar methods with optical power efficiency derived from DCO- or ACO-OFDM techniques that have been studied only in Optical Wireless Communications (OWC) context.

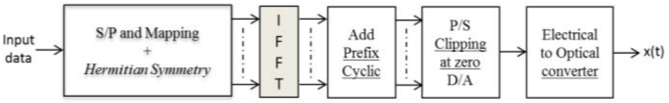


Fig. 1. Block diagram of an ACO-OFDM transmitter.

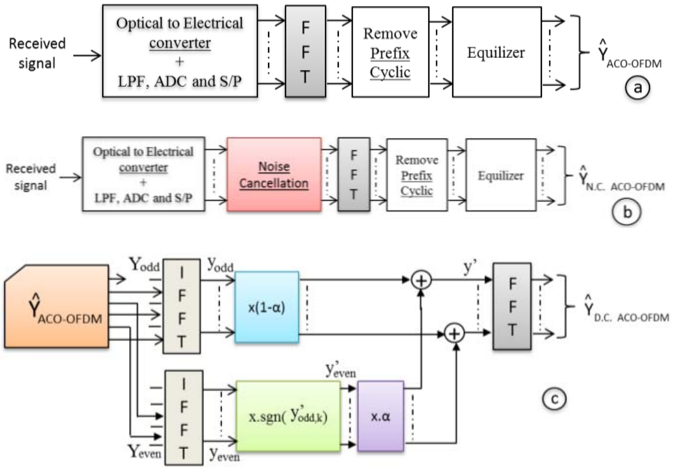
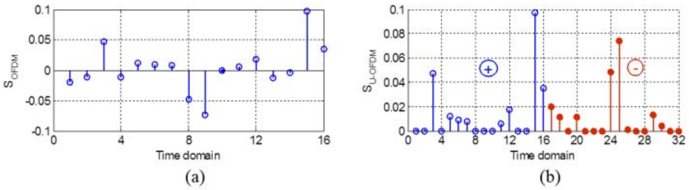


Fig. 2. Block diagram of: (a)- ACO-OFDM receiver, (b)- Noise Cancellation ACO-OFDM receiver, and (c)- Diversity-combined ACO-OFDM receiver.



(a) (b)

Fig. 3. (a)- Typical real OFDM time domain signal, (b)- U-OFDM time domain signal.

A. *Noise cancellation ACO-OFDM*

Noise cancellation method for ACO-OFDM has been first introduced in [8] and then in [12]. It operates on the noise and has similar transmitter block diagram as the conventional ACO-OFDM (Fig. 1). There is no change in terms of optical output power. The only difference is the noise cancellation process applied to the received signal before the FFT (Fig. 2(b)). The resulting time sequence x[n] after performing the IFFT, is shown to satisfy an anti-symmetry given by (1) where N is the FFT size.

$$x[n] = -x\left[n+\frac{N}{2}\right]; \qquad n = 0,1,\cdots,\frac{N}{2}-1 \tag{1}$$

Like the transmitted IM/DD signal is non-negative and the channel noise added to it (in electrical domain) is bipolar, the anti-symmetry of the times 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. Occasionally, the wrong samples will be selected. But, it is shown that maximum gain of up to 3dB in optical power can be achieved over ACO-OFDM [12] in flat AWGN channel.

B. *Diversity-combined ACO-OFDM*

A different approach to Noise cancellation ACO-OFDM is diversity-combined ACO-OFDM [9] which operates on the received signal. D.C. ACO-OFDM uses the same transmitter as conventional ACO-OFDM. But at the receiver, both odd and even subcarriers are used after equalization as shown in Fig. 2(c). The signals $y'_{even,k}$ on the even subcarriers are recovered after a non-linear process [11] of $y_{even,k}$ and combined with the signal on odd subcarriers $y_{odd,k}$ with a weighting factor α wisely chosen, as shown in [12] and given by:

$$y'_{even} = \mathrm{sgn}(y_{odd,k}) \times y_{even,k} \tag{2}$$

$$y'_k = (1-\alpha)y_{odd,k} + \alpha y'_{even,k} \qquad 0 \le \alpha \le 1 \tag{3}$$

It is shown in theory [12] 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 to be 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 flat AWGN channel and shown to be insensitive to the variations in the zeroth subcarrier due to the DC-offset [12]. Each of these methods makes an estimation of zeroth subcarrier at the receiver. In the first method (4), the DC value of the signal is estimated using the statistical relationship between x^2 and x. The DC value in the second method (5) is estimated by reconstructing the even signal using the odd signal. It is shown that both techniques give better performance than conventional ACO-OFDM.

$$\hat{Y}_0 = \sqrt{E\{x^2_{ACO,k}\}/\pi} = E\{x_{ACO,k}\} \tag{4}$$

$$\hat{Y}_0 = \sum_{k=0}^{N-1} y_{even,k} = \sum_{k=0}^{N-1} \left| y_{odd,k} \right| \qquad (5)$$

C. *Unipolar OFDM*

The third proposed modulation scheme, U-OFDM [14], is inspired by the concept from [15] in attempt to close the 3dB gap between OFDM and ACO-OFDM for bipolar signals, whilst generating a unipolar signal, which does not require the biasing of DCO-OFDM [4] for OWC. We know that unipolar signals do not require a DC shift and lead to higher power efficiency. U-OFDM is a simple alternative technique to ACO-OFDM which provides the benefit of unipolar signals. The modulation process begins with conventional modulation of an OFDM signal. The only difference is that the real bipolar OFDM signal obtained such as in Fig. 3(a) is transformed into a unipolar signal by encoding each time sample into a pair of new time samples. If the original OFDM sample is positive, the first sample of the new pair is set as “active”, and the second “inactive”. If, on the other hand, the original OFDM sample is negative, the first sample of the new pair is set “inactive” and the second “active”. Active samples are set equal to the absolute value of the original OFDM sample they correspond to, and inactive samples are set to zero. The U-OFDM signal is obtained when the first samples of each pair are grouped in their original order to form the called “positive” block while the second samples are grouped in the called “negative” block as shown in Fig. 3(b). Then the positive block is sent first and the negative block is transmitted second through the channel. Since the length of the OFDM frame is doubled, the spectral efficiency of U-OFDM is about half the spectral efficiency of DCO-OFDM and the same as the ACO-OFDM. At the reception, a simple and efficient way to demodulate is to compare the amplitudes of the corresponding received samples in each pair: the one with higher amplitude will be marked as “active”. In [14], performance of U-OFDM has been simulated in a flat AWGN channel of OWC systems. It is shown that U-OFDM has better performance than ACO-OFDM of the same modulation order and its performance improvement reaches almost 3dB for higher order M-QAM.

We will use all the presented methods in the SSMF fiber link for PON context in order to show their advantages in terms of performances and fiber length increase.

III. DESCRIPTION OF SIMULATED PON IM/DD MODEL

Fig. 4 depicts the simulated 10Gbps OFDM IM/DD PON fiber link where the optical budget (optical power difference between IN-channel and OUT-Channel) can be chosen in order to evaluate if the performance is compatible with the NGPON2 normalization [3]. The generated OFDM signal modulates an analog 1550nm DFB-Laser of 4.4dBm optical power and is transmitted through SSMF (G-652) fiber before being detected and low pass filtered at reception by a PIN photodiode with a transimpedance amplifier. Prefix cyclic of 1/32 is used with IFFT/FFT length of 512 and simulations are realized with realistic components parameters as set in TABLE I. Simulations are performed with VPItransmissionMaker™ 8.7 and both OFDM modulator and demodulator blocks are implemented with MATLAB®. According to M-QAM order, the bit error rate (BER) is performed (6) thanks to the EVM calculation as in [16].

$$BER \approx \frac{2\left(1-\frac{1}{\sqrt{M}}\right)}{\log_2(M)} * erfc\left(\frac{\sqrt{\frac{3}{2(M-1)}}}{EVM}\right) \qquad (6)$$

TABLE I
OPTICAL CHANNEL PARAMETERS

PARAMETERS	Values
Wavelength	1550 nm
Light source	4.4dBm Analog DFB-Laser
Laser rin	-157 dB
Laser bias current	30 mA
Laser threshold current	25 mA
Laser henry factor	2.5
Laser bandwidth	17 GHz, 4th Bessel LPF
Laser slope efficiency	0.2 W/A
Photodetector	PIN-TIA 54dBΩ
PIN dark current	5 nA
PIN-TIA bandwidth	20 GHz, 4th Bessel LPF
Thermal noise	21 pA/Hz$^{1/2}$
PIN responsivity	0.7 A/W
Fibre type	SSMF, G-652
Fiber non-linear coefficient	2.6x10^{-20} m^2/W
Chromatic dispersion coefficient	17 ps/km/nm
Fiber loss	0.2 dB/km

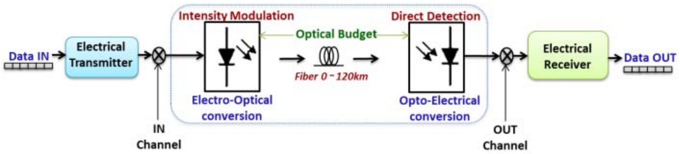


Fig. 4. Simulated PON IM/DD OFDM system.

IV. SIMULATIONS RESULTS AND DISCUSSIONS

A. *Performance in an AWGN flat channel*

In this first section, we draw the performance of all studied unipolar OFDM techniques for the case of flat AWGN channel with any consideration of optoelectronic component parameters. The OFDM optical power is fixed to the unity.

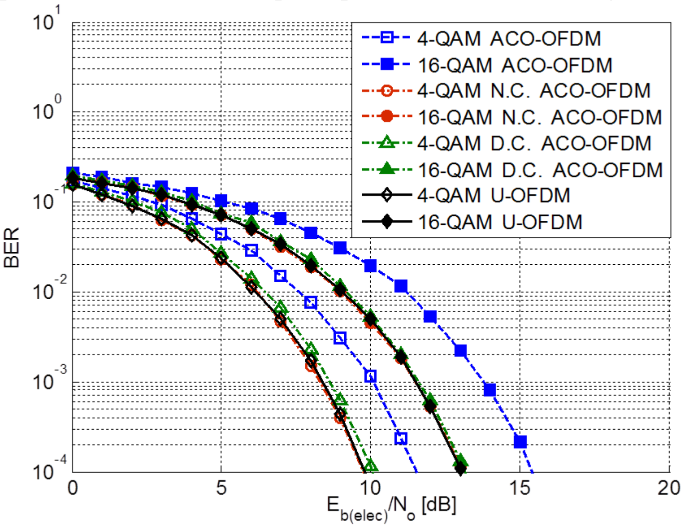


Fig. 5. BER versus $E_{b(elec)}/No$ of 4-QAM and 16-QAM unipolar OFDM.

The goal is to validate our simulation methodology. It is noticeable to observe with results of Fig. 5 that all derived unipolar OFDM modulations have almost the similar performance for the same M-QAM constellation. They also perform better performance than conventional ACO-OFDM in terms of electrical signal-to-noise ratio per bit. The performance improvement reaches 1.75dB for 4-QAM format to 2.5dB for 16-QAM format. These results confirmed results obtained in [10], [12] for flat AWGN channel and permit to validate our implementation. The current results demonstrate that these new modulations provide the same benefits as the conventional ACO-OFDM modulation scheme but with an improved demodulation scheme for better power efficiency in AWGN channel.

B. Performance in PON IM/DD fiber link

Performance comparison of all unipolar methods has been simulated here for the context of PON IM/DD fiber link, with taking into account realistic components parameters as defined in TABLE I.

It is important to notice that the frequency response of the used channel has a chirped shape as mentioned in [17]. Fig. 6 presents the behavior of the simulated channel which is not flat, contrary to the case of section IV-A but presents lobes. As it is shown in [17], when increasing the fiber length for a fixed laser henry factor value, the system's resonance frequencies will shift left and the transmission lobes will narrow. So, the chirped optical fiber channel induces the transmission lobes to be narrowed and frequency selective with the increase of the fiber length.

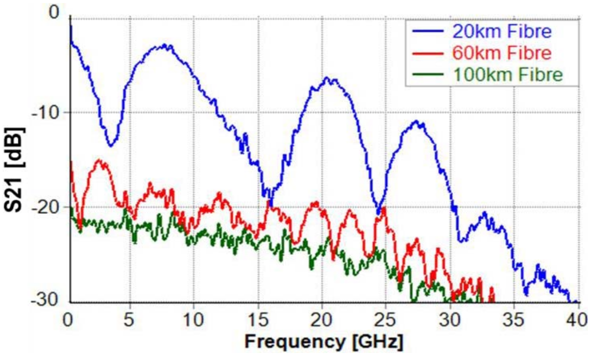


Fig. 6. Frequency response variation with the fiber length of the simulated IM/DD fiber link.

1) Optical budget and received power comparison

As the modulation scheme of N.C. ACO-OFDM, D.C. ACO-OFDM and ACO-OFDM is the same, the transmitted electrical and optical powers are unchanged. In our simulation, the emitted laser power is 4.4dBm. Fig. 7 shows the simulation results of the BER performance in terms of the received optical power when 4-QAM format is used with each unipolar OFDM scheme for fiber span of 60km. It is seen that diversity-combined ACO-OFDM gives the best BER performance in comparison to all modulation schemes. Noise cancellation ACO-OFDM and U-OFDM performances are almost similar but not better than conventional ACO-OFDM. The raison for these results is proved in [17] and explained here by the behavior of the channel response plotted in Fig. 6. In that case, the transmitted signal is distorted due to the channel impact and then noise cancellation ACO-OFDM or U-OFDM demodulation scheme results to errors compared with signal non-linear operation made by D.C. ACO-OFDM.

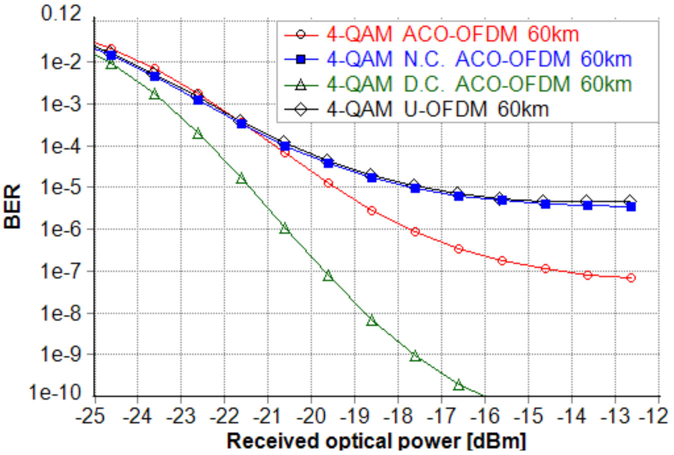


Fig. 7. BER against received optical power with 4-QAM constellation.

Hence, with PIN sensitivity of -21dBm, BER value of 10^{-4} can be achieved using ACO-OFDM, N.C. ACO-OFDM and U-OFDM while D.C. ACO-OFDM gives BER improvement of 1.7 decade over ACO-OFDM, i.e., $3x10^{-6}$. But when the received power is high (more than -21dBm), both U-OFDM and N.C. ACO-OFDM degrade, compared to ACO-OFDM. To achieve BER of 10^{-3} (good enough with the use of forward error codes), the received power is -23.3dBm with D.C. ACO-OFDM to almost -22.2dBm with all the remaining OFDM schemes. The sensitivity gain is then 1.1dB. These results put into evidence that, a data rate transmission of 10Gbps with optical budget of 26.6dB can be achieved with all unipolar OFDM schemes until 60km distance.

In order to be in accordance with the specifications of NGPON2, in the rest of this paper, we fix the optical budget to 25dB corresponding to a split ratio of 128 in PON topology. The challenge is now to evaluate the highest distance that can be achieved.

2) Transmission distance comparison

Using 4-QAM format at data rate of 10Gbps with 25dB of optical budget, Fig. 8 shows results of the BER versus transmission distance for two different realistic values of the 20GHz PIN photodiode thermal noise.

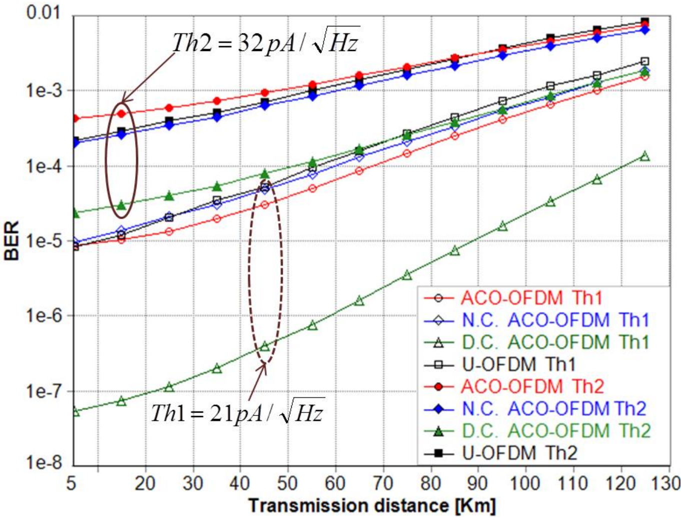


Fig. 8. BER against transmission distance for two values of Photodiode thermal noise.

We can see that the BER degrades with the increase of the transmission distance due to the chromatic dispersion of the optical fiber. We observe here that, when thermal noise increases from value of $21pA/\sqrt{Hz}$ to $32pA/\sqrt{Hz}$, the BER of N.C. ACO-OFDM and U-OFDM are little improved than ACO-OFDM. We also see that with thermal noise value of $21pA/\sqrt{Hz}$ for BER of 10^{-3}, it is possible to realize transmission distance through 101.6km, 108.5km and 114.6km with respectively U-OFDM, N.C. ACO-OFDM and ACO-OFDM while more than 120km (our simulation limit) can be reached with D.C. ACO-OFDM. However, when the thermal noise becomes important $32pA/\sqrt{Hz}$, the transmission distance reduces considerably for all OFDM schemes. A fair comparison at BER of 10^{-3} with the case of $21pA/\sqrt{Hz}$, shows that all derived unipolar OFDM schemes reach better transmission distance than conventional ACO-OFDM. As for example, only distance of 47.7km can be reached by conventional ACO-OFDM whereas U-OFDM, N.C. ACO-OFDM and D.C. ACO-OFDM can reach distances of 54.5km, 60.3km and 109.4km respectively. These results show the noise impact of the receiver frond-end on the system performance and then explain why the transmission distance is now better in both U-OFDM and N.C. ACO-OFDM than conventional ACO-OFDM. An interesting observation to note is that, with BER of 10^{-3} and thermal noise of $32pA/\sqrt{Hz}$, the distance transmission of D.C. ACO-OFDM is at least doubled of the conventional ACO-OFDM distance.

V. CONCLUSION

We analyzed and compared the performance of known unipolar OFDM methods for PON IM/DD fiber link using realistic components parameters in terms of received power and distance transmission. It is important to notice that these comparisons have been given considering the same transmitter optical output power that means the same power consumption. 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 significantly improved the performance of ACO-OFDM for PON fiber link because it permits to achieve at least double the transmission distance. Then, we concluded that it enables to efficiently compensate frequency selective distortion of optical fiber link channel. We also showed that data rate of 10Gpbs with split ratio of 128 using 4-QAM format can be sent through 60km fiber link with Noise cancellation ACO-OFDM to more distance, i.e., 109km with D.C. ACO-OFDM. We observed that although its complexity cost (two successive OFDM symbol blocks correspond to only one original OFDM symbol), U-OFDM scheme which is shown to be both optically and electrically more power efficient in a flat AGWN channel can only reach almost the same performance as Noise cancellation ACO-OFDM in an optical fiber link. Regarding to the noise effect of the PIN component, noise cancellation ACO-OFDM or U-OFDM can be used instead of the conventional ACO-OFDM. The impact of other component parameters will be studied in our future work and compared with DCO-OFDM.

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