# D-C ACO-OFDM and DCO-OFDM for Passive Optical Network: Performance Comparison in IM/DD Fiber Link

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***Abstract*— We present a comparative study of Diversity-Combined Asymmetrically Clipped Optical OFDM (D-C ACO-OFDM) and DC-biased Optical OFDM (DCO-OFDM) techniques in 17Gbps intensity modulated and direct detected (IM/DD) fiber link of passive optical network (PON). From simulation results obtained with realistic components parameters, we find that D-C ACO-OFDM offers an improved demodulation than DCO-OFDM. Using 4QAM format and split ratio of 1x32, D-C ACO-OFDM is showed to reach 45.3km distance which is almost the double distance transmission of DCO-OFDM with the same modulation order. We also show at BER of $10^{-3}$, that 20km transmission distance can be reached at 24Gbps 4QAM D-C ACO-OFDM data rate and then D-C ACO-OFDM is a suitable efficient cost-effective solution for GPON deployment with benefit of use of low-cost laser bandwidth in comparison with DCO-OFDM. At the same BER performance, in comparison with D-C ACO-OFDM at high bit rates transmission, DCO-OFDM promises to deliver higher throughput. The Bit Error Rate (BER) performance value is fixed to $10^{-3}$ (limit value when Forward Error Codes are used).**

***Keywords—Optical OFDM; IM/DD; PON; BER.***

## I. Introduction

Recently, with new services such as Internet Protocol TV (IPTV), Video-on-Demand (VoD), online gaming and other emerging applications, the bandwidth demand is increasing rapidly. This increase in bandwidth demand and all service support capabilities as well as enhanced performance transmission can be addressed to some extent by passive optical networks (PON). A passive optical network [1] is a form of fiber optic access network. The first next-generation PON [2] (NG-PON1) should leverage the use of existing Giga-PON ODN (Optical Distribution Network) to control cost. The Full Service Access Network (FSAN) defined NG-PON1 [3] as an asymmetric 10G system (rates of 10Gbps downstream and 2.5Gbps upstream) with split ratio at least 64 over at least maximum 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 with the use of NRZ-TWDM. Beyond this second phase (NG-PON2) [3], modulation formats with higher spectral efficiency than NRZ are planned, such as: CDMA, WDM and multi-carriers modulations (like OFDM) [4]. As a technique well employed in wired and wireless communications, Orthogonal Frequency Division Multiplexing (OFDM) has recently attracted many research focuses in the optical communications and access networks. Many optical systems communications use intensity modulated/direct detection (IM/DD) because it is less expensive. In IM/DD systems, the electrical signal is modulated onto intensity of the optical carrier. Then, only real and non-negative signals can be transmitted [6]. One way to get real signal at the transmitter is the use of inverse fast Fourier transform (IFFT) which input is constrained to have Hermitian symmetry at the expense of half of the spectral efficiency. Two OFDM methods are often used for generating non-negative signals. One is called DC-biased Optical OFDM (DCO-OFDM) [3], [6] and the second, Asymmetrically Clipped Optical OFDM (ACO-OFDM) [7]-[8]. In Optical Wireless Communications (OWC), different alternative techniques with optical power efficiency exist and derive from DCO- and ACO-OFDM. We have: Noise cancellation ACO-OFDM (NC ACO-OFDM) where a noise cancellation process [9] is operated at the demodulation using anti-symmetry property of the received signal and Diversity-combined ACO-OFDM (D-C ACO-OFDM) [10]-[11] which is further described in the next section. In this paper, we investigate the performance comparison of Diversity-Combined ACO-OFDM and DC-biased Optical OFDM methods in context of IM/DD PON fiber link. Simulation results are presented taking into account realistic component models and parameters issued from experimental characterization [12] realized in the framework of ANR/EPOD project. The rest of the paper is organized as follows: we provide an overview of both DCO-OFDM and D-C ACO-OFDM in the first section. A description model of simulated PON IM/DD fiber link is presented in Section III. Simulation results and discussions are given in Section IV for the case of real PON fiber link with 1xM optical splitter, where M is the number of ONUs (Optical Network Unit) that share the same physical medium (optical fiber). Finally, Section V concludes the paper.

## II. Optical IM/DD OFDM Schemes

The first known OFDM technique in optical IM/DD systems communications is DC-biased optical OFDM. In DCO-OFDM, the signal is made positive by adding a DC bias value to the IFFT bipolar signal output after mapping and data carriers modulation. This bias value 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 (PAPR) of OFDM signals, a very high bias would be required to eliminate all negative peaks. Instead, a moderate bias is normally used (practically 7dB) and the remaining negative peaks are clipped, resulting in clipping noise in both even and odd subcarriers. The block diagrams for DCO-OFDM transmitter and receiver is presented in Fig. 1.

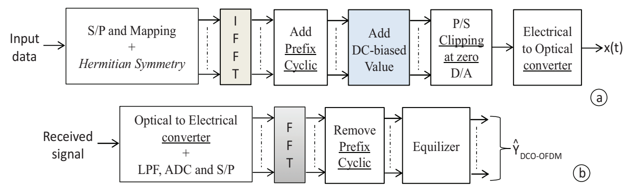


Fig. 1. Block diagrams of DCO-OFDM scheme: (a)-transmitter, (b)-receiver.

An optical power efficient alternative to DCO-OFDM is ACO-OFDM [8] where data are carried and mapped to only the odd IFFT subcarriers inputs with all the even inputs set to zero. The resulting bipolar signal at the IFFT output is clipped at zero to give a non-negative signal. Clipping noise [8] affects only the unused even subcarriers, but not the odd subcarriers. Such as only half of the subcarriers are used to carry data, ACO-OFDM has half of the spectral efficiency of DCO-OFDM. Fig. 2 presents a transmitter and receiver block diagrams of an ACO-OFDM system.

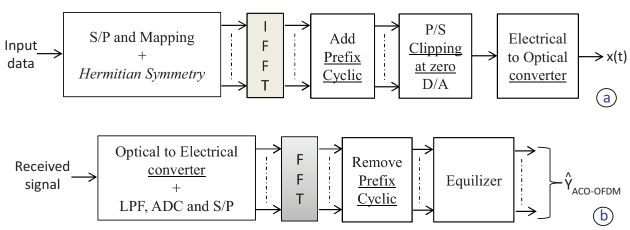


Fig. 2. Block diagrams of ACO-OFDM scheme: (a)-transmitter, (b)-receiver.

Another efficient method of ACO-OFDM is Diversity-Combined ACO-OFDM [10]. This new approach operates on the received signal without change of the transmitter like in conventional ACO-OFDM. But at the receiver, both odd and even subcarriers are used after conventional ACO-OFDM equalization resulting to demodulated D-C ACO-OFDM signal as depicted at Fig. 2. It can be seen that the equalized conventional $\hat{Y}_{ACO-OFDM}$ signal is divided into odd and even parts ($Y_{odd}$ and $Y_{even}$) that are each one input into an IFFT to produce in time domain, signals $y_{odd}$ and $y_{even}$. The resulting signal $y'_{even,k}$ on the k[th] even subcarrier is recovered after non-linear process [11] of known $y_{even,k}$ and then combining with signal $y_{odd,k}$ on the k[th] odd subcarrier using a weighting factor α wisely chosen, as in [13] by:

$$y'_{even} = \mathrm{sgn}(y_{odd,k}) \times y_{even,k} \tag{1}$$

$$y'_k = (1-\alpha) y_{odd,k} + \alpha y'_{even,k} \qquad 0 \le \alpha \le 1 \tag{2}$$

In order to make the method insensitive against variations in the zeroth subcarrier, an estimation of the DC-offset is done as shown in Fig. 3 by using one of formulas (3) and (4). In the first expression (3), the DC-offset value of the signal is estimated using the statistical relationship between $x^2$ and $x$. The DC-offset value in the second expression (4) is estimated by reconstructing the even signal component using the odd signal one.

$$\hat{Y}_0 = \sqrt{E\{x^2_{ACO,k}\}/\pi} = E\{x_{ACO,k}\} \tag{3}$$

$$\hat{Y}_0 = \sum_{k=0}^{N-1} y_{even,k} = \sum_{k=0}^{N-1} \left| y_{odd,k} \right| \tag{4}$$

By this way, gain of up to 3dB in electrical power is shown to be achieved over ACO-OFDM through flat channel with AWGN in OWC [13].

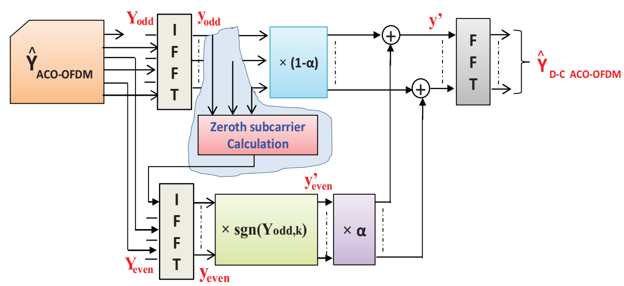


Fig. 3. Receiver block diagram of Diversity-combined ACO-OFDM.

## III. SIMULATION DESCRIPTION OF THE IM/DD PON LINK

In this section, we present the simulated IM/DD fiber link model. Fig. 4 depicts diagram block of the simulated 17Gbps IM/DD fiber link where a variable optical attenuator (VOA) is used in order to emulate the optical split as in NG-PON2 normalization [3]. The OFDM signal modulates a 1550nm analog Laser 1915 LMA series and then is transmitted through SSMF G-652 fiber before being detected and lowpass filtered at reception by a 20GHz PIN photodiode with transimpedance amplifier (TIA). The IFFT/FFT size is 512 and prefix cyclic of 1/32 is used to reduce inter-symbol interference (ISI). The simulations are performed with VPItransmissionMaker™ 8.7 using realistic components parameters given in TABLE I. The emitted power is of 7.3dBm for DCO-OFDM and 3.6dBm for D-C ACO-OFDM (because of the zeroth clipped processing made at the IFFT output without the DC-bias). Both OFDM modulator and demodulator blocks are implemented in MATLAB®. According to M-QAM constellation, the bit error rate (BER) is computed (5), thanks to the EVM calculation as in [14].

$$BER \approx \frac{2\left(1-\frac{1}{\sqrt{M}}\right)}{\log_2(M)} * erfc\left(\sqrt{\frac{3}{2(M-1)}}\frac{1}{EVM}\right) \qquad (5)$$

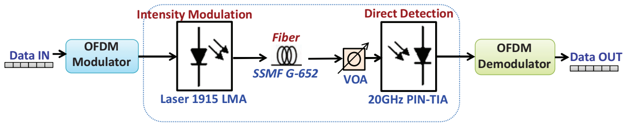


Fig. 4. Simulated IM/DD PON fiber link.

TABLE I. OPTICAL CHANNEL

| Optical fiber link parameters | |
|---|---|
| ***Parameters*** | ***Values*** |
| Transmission wavelength | 1550 nm |
| **Light source** | Analog DFB-Laser |
| Laser RIN | -157 dB |
| Laser bias current | 25 mA |
| Laser threshold current | 20 mA |
| Laser henry factor | 2.5 |
| Laser bandwidth | 17 GHz, 4th Butterworth LPF |
| Laser slope efficiency | 0.138 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 | 0.9 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 |
| Weighting factor in D-C ACO-OFDM | 0.50 |

## IV. Results and Discussions

Results obtained with methods described in Section II, are presented here, for SSMF fiber link. In general, because of the OFDM frame structure, D-C ACO-OFDM achieves half the spectral efficiency of DCO-OFDM for same modulation order. Therefore, in addition to 4QAM D-C ACO-OFDM, 16QAM D-C ACO-OFDM is simulated against a 4QAM DCO-OFDM scheme to compare the BER performance at a similar spectral efficiency of 1bit/s/Hz.

The frequency response of the simulated channel presents a chirped shape as plotted in Fig. 5.

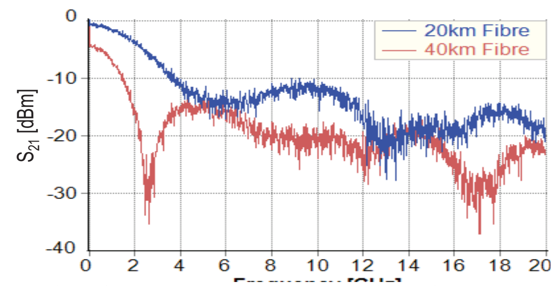


Fig. 5. Channel frequency response variation with the fiber span.

It is shown in [15] that, 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. Hence, we have an example of frequency selective channel.

### *A. Performance in terms of optical split loss*

The BER performance of D-C ACO-OFDM and DCO-OFDM is compared in terms of the optical split loss values in Fig. 6.

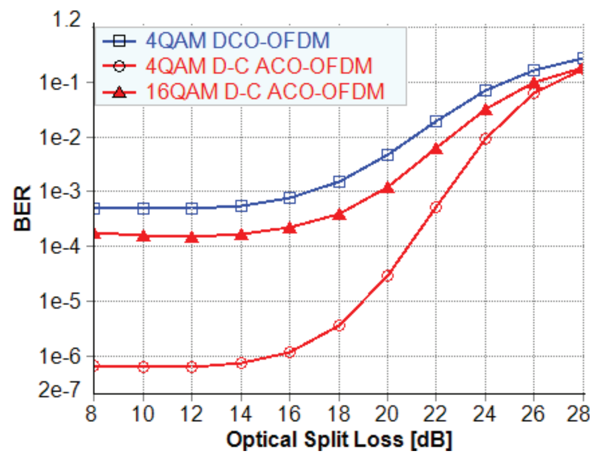


Fig. 6. BER versus optical split loss for 4QAM DCO-OFDM and 4/16-QAM D-C ACO-OFDM at 20km of fiber span.

It is shown that the simulated 4/16-QAM D-C ACO-OFDM scheme has noticeably better BER performance than the 4QAM DCO-OFDM although the efficient optical power in D-C ACO-OFDM. This is due first, to the clipping noise generated in both even and odd subcarriers in DCO-OFDM which is reduced or cancelled by the improved demodulator in D-C ACO-OFDM. Also, as the channel response is selective according to Fig. 5, only method which operates on the received signal as diversity-combined process [11] can reach better BER. However, a comparison between 4QAM and 16QAM D-C ACO-OFDM suggests that higher order QAM modulation is more vulnerable to signal clipping and distortion. This is because the noise induced to the signal is added independently of the M-QAM modulation order. Hence, for a BER value of $10^{-3}$, the maximum optical split loss allowed at 20km fiber span is 16.8dB for 4QAM DCO-OFDM to respectively 22.5dB and 19.6dB for respectively 4QAM and 16QAM D-C ACO-OFDM. For a given optical split loss, D-C

ACO-OFDM system can reach BER improvement of almost one decade over DCO-OFDM for similar spectral efficiencies to almost 3 decades for same modulation order.

In the rest of this paper, optical split loss of 15dB is set to emulate split ratio of 1x32 users as it is considered in PON context.

### B. *Performance in terms of transmission distance*

With split loss of 15dB, Fig. 7 presents the performance comparison of D-C ACO-OFDM vs. DCO-OFDM in terms of transmission reach. It is also seen that D-C ACO-OFDM outperforms DCO-OFDM over all transmission distance. For the same modulation order (4QAM), D-C ACO-OFDM offers better BER values than DCO-OFDM. This is explained by the fact that as the optical channel is frequency selective with the fiber length, the OFDM method which is more sensitive to clipping noise will more likely to be degraded. For same spectral efficiency, 16QAM D-C ACO-OFDM achieves almost the same BER performance as 4QAM DCO-OFDM for low transmission distance but gives good BER performance than 4QAM DCO-OFDM and degrades in the same manner as 4QAM D-C ACO-OFDM when the distance increases. When the modulation order increases the signal bandwidth will narrow for constant bit rate. Thus, for distance transmission less than 20km, the channel behavior (Cf. Fig. 5) is almost constant or less selective than when distance increases. Then, for BER value of $10^{-3}$, maximum reach of 23km can be reached with 4QAM DCO-OFDM for respectively 45.2km and 40.8km with respectively 4QAM and 16QAM D-C ACO-OFDM.

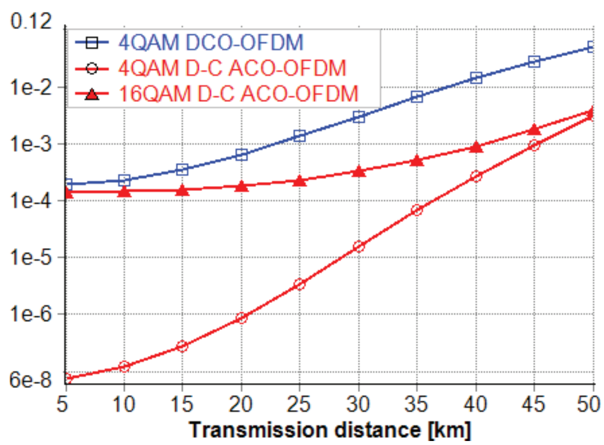


Fig. 7. BER versus transmission distance for 4QAM DCO-OFDM and 4/16-QAM D-C ACO-OFDM.

### C. *Performance in terms of bit rate transmission*

The bit rate comparison is explored in Fig. 8 for both D-C ACO-OFDM and DCO-OFDM at 20km fiber span and split loss of 15dB. It is shown that 4QAM D-C ACO-OFDM allows good bit rate transmission at any BER values. It is also seen in the case of same spectral efficiency that bit rate values of more than 13Gbps can be reached with 16QAM D-C ACO-OFDM over 4QAM DCO-OFDM. For example, at BER value of $10^{-3}$, bit rate of 17.8Gbps can be transmitted with 4QAM DCO-OFDM for respectively 24Gbps and 22.4Gbps with respectively 4QAM D-C ACO-OFDM and 16 QAM D-C ACO-OFDM. An important observation concerns the bit rate performance at 20km for BER value of $10^{-9}$. We can see that value of 14Gbps data rate can be reached with 4QAM D-C ACO-OFDM to only 2.5Gbps with DCO-OFDM of the same spectral efficiency. And then, the throughput performance of D-C ACO-OFDM outperforms DCO-OFDM. This implies that D-C ACO-OFDM is an efficient cost-effective solution scheme for GPON access networks where maximum reach of 20km and bit rate of 2.5Gbps are needed with split ratio of 1x32. Unfortunately for high data rates, as in comparison to 4QAM DCO-OFDM, 4QAM D-C ACO-OFDM achieves good BER performance with an increase in the optical power efficiency at the expense of a 50% reduction in spectral efficiency. But in terms of throughput performance, the DCO-OFDM scheme delivers a better BER performance.

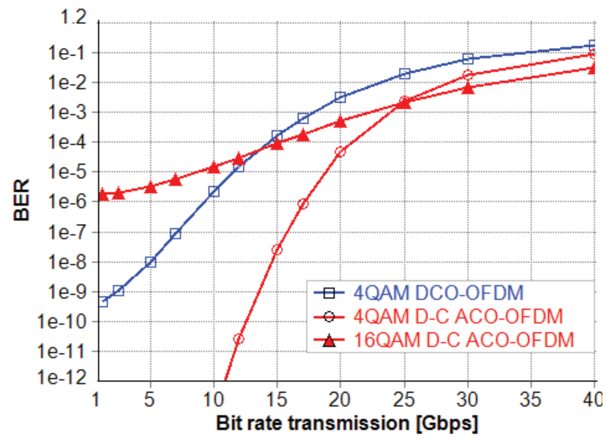


Fig. 8. BER versus bit rate transmission for 4QAM DCO-OFDM and 4/16-QAM D-C ACO-OFDM at 20km of fiber span.

### D. *Laser bandwidth impact*

The performance impact of the laser bandwidth is presented at 20km for both D-C ACO-OFDM and DCO-OFDM in Fig. 9.

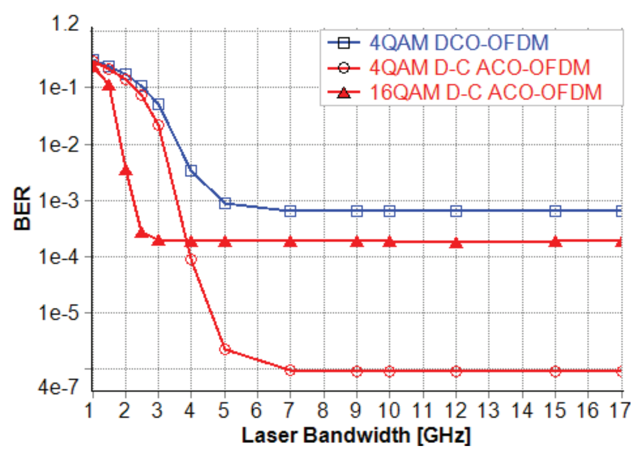


Fig. 9. BER against laser bandwidth for 4QAM DCO-OFDM and 4/16-QAM D-C ACO-OFDM at 20km of fiber span.

It is seen that both BER performances improve with the laser bandwidth increase but become constant from value of 8GHz for the same modulation order and 4GHz for 16QAM D-C ACO-OFDM. This is because of the signal lowpass filtering nature of the optical laser source as the signal bandwidth is 8.5GHz for 4QAM and 4.25GHz for 16QAM at data rate of 17Gbps. Also for high bandwidth values, it can be seen that the D-C ACO-OFDM delivers better BER performance than DCO-OFDM with BER improvement of almost 0.5 decade for the same spectral efficiency to up to 3 decades for same modulation order. For BER value of $10^{-3}$, only laser bandwidth value of 2.4GHz is needed for 16QAM D-C ACO-OFDM while bandwidth values respectively of 3.6GHz and 5GHz are needed for respectively 4QAM modulation of D-C ACO-OFDM and DCO-OFDM. Also, the results of Fig. 9, show the BER improvement of D-C ACO-OFDM with the use of low-cost laser bandwidth in comparison with DCO-OFDM.

## V. Conclusion

In this paper, performance comparison of 17Gbps Diversity-combined ACO-OFDM and DCO-OFDM schemes is studied and compared for PON IM/DD fiber link using realistic components parameters. We found at BER of $10^{-3}$ and split ratio of 1x32, that 45.3km of fiber length can be reached with D-C ACO-OFDM for almost the half (23km) with DCO-OFDM of the same modulation order. It is shown for 20km distance that for BER value of $10^{-3}$, data rate of 24Gbps is allowed with 4QAM D-C ACO-OFDM for 17.8Gbps with 4QAM DCO-OFDM and 22.4Gbps with 16QAM D-C ACO-OFDM. As for BER of $10^{-9}$, 14Gbps data rate is reached with 4QAM D-C ACO-OFDM to only 2.5Gbps with 4QAM DCO-OFDM, we found that D-C ACO-OFDM is an efficient cost-effective solution for GPON networks over DCO-OFDM because of its throughput performance and lower radiated average optical power. In comparison with D-C ACO-OFDM of the same BER, the DCO-OFDM scheme promises to deliver higher throughput at high bit rates transmission. We also showed that D-C ACO-OFDM allows the use of low-cost laser bandwidth in comparison with DCO-OFDM. Hence, in our future work, the impact of other components parameters and the signal power will be studied and compared for both schemes.

## References

[1] H. Song et al., "Long-Reach Optical Access Networks: A Survey of Research Challenges, Demonstrations, and Bandwidth Assignment Mechanisms", *IEEE Communications Surveys and Tutorials*, Vol. 12, No. 1, 2010.

[2] A. M. Ragheb, H. Fathallah, “Performance analysis of next generation-PON (NG-PON) architectures,” *High Capacity Optical Networks and Enabling Technologies (HONET)*, pp. 339-345, 2011.

[3] Analysys mason, “Fibre capacity limitations in access networks,” *Canal Court, 40 Craiglockhart Avenue Edinburg EH14 1LT, Scotland, 2010*. [Online]. Available: http://stakeholders.ofcom.org.uk/binaries/research/technology-research/fibre.pdf

[4] J. Armstrong, “OFDM for optical communications,” *Journal of Lightwave Technology*, vol. 27, no. 3, Feb. 2009.

[5] R. Hu, Qi Yang, and al., “Direct-detection optical OFDM superchannel for long-reach PON using pilot regeneration,” *Optics Express*, vol. 21, issue 22, pp. 26513-26519, 2013.

[6] J. M. Tang, P. M. Lane, and K. A. Shore, “Transmission performance of adaptively modulated optical OFDM signals in multimode fiber links,” *IEEE Photon. Technol. Lett.*, vol. 18, no. 1, pp. 205-207, Jan. 2006.

[7] J. Armstrong, B. J. C. Schmidt, “Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN,” *IEEE Commun. Lett.*, vol. 12, no. 5, pp.343-345, 2008.

[8] J. Armstrong, A. Lovery, “Power efficient optical OFDM,” *Electronics Letters*, vol. 42, no. 6, Mars 2006.

[9] Asadzadeh K., Dabbo A., and Hranilovic S., "Receiver design for asymmetrically clipped optical OFDM," *GLOBECOM Workshops (GC Wkshps), 2011 IEEE*, vol., no., pp.777-781, 5-9 Dec. 2011.

[10] L. Chen, B. Krongold, and J. Evans, “Diversity combining for asymmetrically clipped optical OFDM in IM/DD channels,” in *Proceedings IEEE GLOBECOM*, Honolulu, Hawaii, pp. 1–6, Dec. 2009.

[11] Dissanayake S.D., Armstrong J., "Novel Techniques for Combating DC Offset in Diversity Combined ACO-OFDM," *Communications Letters, IEEE*, vol.15, no.11, pp.1237-1239, November 2011.

[12] http://www.lightreading.com/optical/optical-components/3s-photonics-boasts-40g-success/d/d-id/675605.

[13] Dissanayake S. D., Armstrong J., Hranilovic S., "Performance analysis of noise cancellation in a diversity combined ACO-OFDM system," *Transparent Optical Networks (ICTON)*, 2012 14th International Conference on, vol., no., pp.1-4, 2-5 July 2012.

[14] R. A. Shafik and al., “On the Error Vector Magnitude as a Performance Metric and Comparative Analysis,” *IEEE-ICET 2006 2nd International Conference on Emmerging Technologies*, Pershavar, Pakistan.

[15] L. A. Neto, P. Chanclou et al., “On the interest of chirped lasers for AMOOFDM transmissions in long distance PON networks,” *Optical Fiber Communication Conference and Exposition (OFC/NFOEC)*, 2011 and the National Fiber Optic Engineers Conference, pp. 1-3, 6-10 March 2011.