https://doi.org/10.25100/iyc.v19i1.2133

TELECOMMUNICATIONS ENGINEERING

Comparison of electronic compensation techniques in access networks with optical phase modulation and coherent detection

INGENIERÍA DE TELECOMUNICACIONES

Comparación de técnicas de compensación electrónica en redes de acceso con modulación de fase óptica y detección coherente

Jesús Álvarez-Guerrero*§, Ferney Amaya-Fernández*

**Faculty of Information and Communication Technologies, Universidad Pontificia Bolivariana. Medellín, Colombia.*
§jesus.alvarezg@upb.edu.co, ferney.amaya@upb.edu.co

(Recibido: Noviembre 09 de 2015 – Aceptado: Agosto 03 de 2016)

Abstract

QPSK modulation format with electronic compensation is an alternative to increase the capacity and reach in the next generation passive optical networks (NG-PON), in response to demanding services and applications. We perform simulations to compare the performance of two electronic compensation techniques Constant Modulus Algorithm (CMA) and Backpropagation, in a NG-PON with QPSK modulation and coherent detection for the compensation of the chromatic dispersion. We use CMA in the access network to increase the data bit rate up to 40 Gb/s and the reach up to 33.5 km, reducing the computational requirements compared with Backpropagation.

Keywords: *Backpropagation algorithm, CMA, coherent detection, fiber optic communication, optical phase modulation.*

Resumen

El formato de modulación QPSK junto a la compensación electrónica es una alternativa para incrementar la capacidad y alcance en las redes ópticas pasiva de próxima generación (NG-PON), en respuesta a la demanda de servicios y aplicaciones. En este documento se presenta la comparación mediante simulaciones del desempeño de dos técnicas de compensación electrónica: el Algoritmo de Módulo Constante (CMA) y el algoritmo Backpropagation en una red NG-PON con modulación QPSK y detección coherente para la compensación de la dispersión cromática de la fibra óptica. Se analiza el uso del algoritmo CMA en la red de acceso con el fin de incrementar la velocidad de transmisión hasta 40 Gb/s y el alcance hasta 33.5 km, reduciendo la complejidad computacional en comparación con el algoritmo Backpropagation.

Palabras Clave: *Algoritmo backpropagation, CMA, comunicaciones por fibra óptica, detección coherente, modulación de fase óptica.*

1. Introduction

Smart cities use Information and Communication Technologies (ICT) to provide infrastructure and public services more interactive to their citizens (Pellicer et al., 2013). In this aspect, smart cities are deploying technologies such as Ubiquitous Sensors Networks (USN), Internet of Things (IoT) (UIT-FG-SSC, 2014), and video applications including 3D video, HDTV and UHDTV, increasing demand on bandwidth and coverage of the access segment in the future communications networks.

Nowadays, Passive Optical Network (PON) is a standardized access network technology that uses On-Off Keying (OOK) modulation format to transmit the information. However, optical phase modulation technique has been proposed to increase the capacity and reach in the access, in response to the demand of services and applications in future smart cities.

PON architecture is a cost-effective alternative to deploy Fiber-To-The-Premises (FTTPs) networks, and Time Division Multiplexing (TDM)-PON is already standardized providing up to 10 Gb/s in the access segment. The main commercialized alternatives of TDM-PON are Ethernet-PON (EPON) standardized by IEEE (IEEE 802.3ah) (IEEE, 2004) and Gigabit-Capable PON (GPON) standardized by ITU-T (ITU-T G.984) (ITU, 2008). EPON provides 1.25 Gb/s between up to 32 users and GPON offers up to 2.5 Gb/s between up to 64 users. The standards 10G-EPON (IEEE 802.3av) (IEEE, 2009) and XG-PON (ITU-T G.987) (ITU, 2012) offers 10 Gb/s downstream bitrate. These standardized PON alternatives use OOK as modulation format.

Next Generation PON (NG-PON) expect at least 40 Gb/s downstream bit rate with up to 60 km of fiber reach and more than 64 end users. NG-PON is not standardized and several alternatives are proposed to increase the reach and capacity compared with standardized alternatives (Muciaccia et al., 2014). Some proposed alternatives include optical amplification (Shim et al., 2013; Zhang et al., 2013), Wavelength Division Multiplexing (WDM) (Ling et al., 2010; Lin, 2008), complex modulation and multiplexing formats, and optical phase modulation (Reis et al., 2011; Kim, 2010). Modulation and multiplexing formats such as Optical Code Division Multiplexing (OCDM) (Kataoka et al., 2011), Orthogonal Frequency Division Multiplexing (OFDM) (Morosi et al., 2016; Neto et al., 2011; Cvijetic et al., 2012), Polarization Division Multiplexing (PDM) (Shim et al., 2013) and Space Division Multiplexing (SDM) (Hernandez et al., 2012) are proposed to be considered in NG-PON.

Optical phase modulation is proposed due to the higher immunity to the optical fiber impairments and higher capacity compared with OOK. There are two alternatives of optical phase receiver: differential detection or coherent detection. Coherent detection presents better performance compared with differential detection. However, it is more complex increasing the cost of the overall system. Differential Phase Shift Modulation (DPSK) has been proposed in the access (Alvarez & Amaya, 2016; Carmona et al., 2015), obtaining higher performance compared with OOK (Latal et al., 2014; Sotiropoulos & de Waardt, 2013). Quadrature Phase Shift Keying (QPSK) is the modulation format used in long haul links with data bit rates up to 56 Gb/s per wavelength per polarization state (Poirier et al., 2015). Additionally, QPSK also has been proposed for the future access network to increase the capacity up to 40 Gb/s (Shim et al., 2013).

Chromatic dispersion and nonlinearities affect the performance of the communication system in NG-PON, due to the data bit rates and the use of several wavelengths (Muciaccia et al., 2014). In this case, electronic compensation techniques should overcome the optical fiber impairments extending the reach and increasing the data bit rate. Backpropagation is the compensation method most used in long haul links, and it was proposed as a universal technique compensating linear and nonlinear fiber propagation effects (Asif et al., 2011; Napoli et al., 2014). However, the main drawback of backpropagation is its excessive computational complexity increasing the cost of the receiver (Napoli et al., 2014). On the other hand, CMA presents lower computational complexity decreasing the requirements of the Digital Signal Processor (DSP) and decreasing the cost of the receiver in the access network. However, backpropagation presents better performance than CMA, obtaining up to 1000 km of fiber length with a 256 Gb/s 16QAM (Quadrature Amplitude Modulation) signal (Maeda et al., 2014). Some authors have proposed CMA for the chromatic dispersion compensation in a NG-PON for data bit rates at 12 Gb/s (Lavery et al., 2015).

In this paper we present simulation results comparing the performance of CMA and backpropagation to compensate the chromatic dispersion in a NG-PON with QPSK phase modulation and coherent detection. We use the Error Vector Magnitude (EVM) as a performance parameter to evaluate the electronic compensation techniques. We use CMA in the access network to increase the data bit rate up to 40 Gb/s with low computational requirements, reducing the cost of the receiver compared with backpropagation obtaining similar performance.

The paper is organized as follows: section 2 presents a description of QPSK phase modulation format and the CMA and backpropagation electronic compensation techniques. Section 3 presents the methodology, including a description of the simulation setup. Section 4 presents the results, and finally, we present the conclusions.

2. Electronic compensation for optical phase modulation

In this section we present a brief description of the QPSK phase modulator transmitter and receiver and the CMA and Backpropagation electronic compensation techniques.

2.1. QPSK modulation and coherent detection

QPSK encode two bits per symbol and each symbol is represented by one of four possible phases of the optical signal. QPSK signal is generated by a quadrature modulator and is demodulated by a coherent detector.

In the transmitter side, the optical phase modulator is composed by a continuous wave Laser Source (LS), an optical splitter, an Optical Combiner (OC), two Mach-Zehnder Modulators (MZMs) and a Phase Modulator (PM) (see Figure 1).

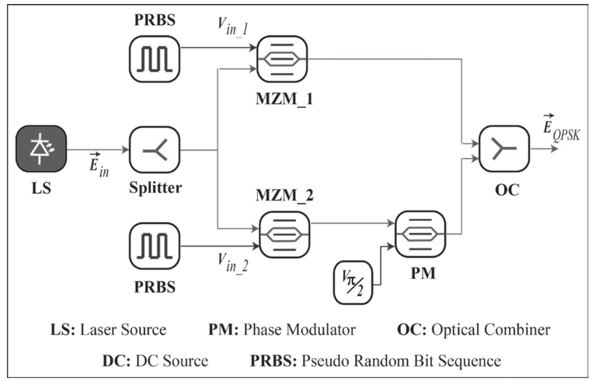

Figure 1. *Optical QPSK Transmitter.*

The transmitter has two arms to generate I (in phase) and Q (quadrature) components of the QPSK signal. In each arm, a MZM modulates the phase of the optical carrier depending on the value of the electrical representation of the bits. A phase modulator introduces a phase shift of 90 degrees over one of the arms to generate the Q component. The combiner receives I and Q components to be transmitted through the optical fiber.

The electrical field of the optical signal at the output of the QPSK transmitter is represented by (Seimetz, 2009):

$$\vec{E}_{QPSK} = \left\{\frac{1}{2}\cos\left(\frac{\Delta\varphi_I(t)}{2}\right) + j\,\frac{1}{2}\cos\left(\frac{\Delta\varphi_Q(t)}{2}\right)\right\}\vec{E}_{in} \quad (1)$$

where $\Delta\varphi_I$ and $\Delta\varphi_Q$ are the induced phase differences of the MZMs in the upper and lower paths and are given by:

$$\Delta\varphi_I(t) = \frac{V_{in\_1}(t)}{V_\pi}\pi \quad (2)$$

$$\Delta\varphi_Q(t) = \frac{V_{in\_2}(t)}{V_\pi}\pi \quad (3)$$

In (2) and (3), V_{in_1} and V_{in_2} are the voltage values of the bits to be transmitted, and V_π is the voltage at the input of the MZM or phase modulator that introduces a phase shift of 180 degrees over the optical signal (Synopsys Group Optical Solutions, 2013).

The receiver (see Figure 2) is composed by a 90 degrees hybrid and two couple of balanced photodetectors to obtain I and Q components of the received signal.

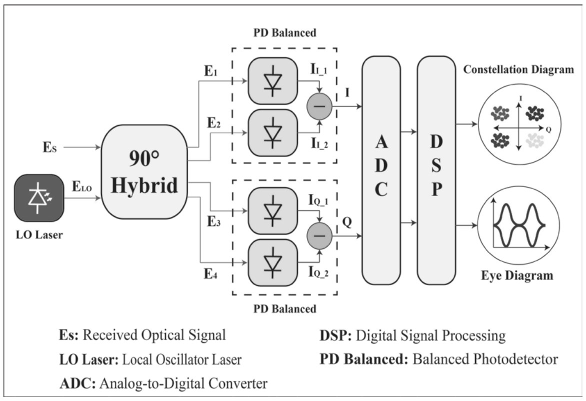

Figure 2. *Coherent QPSK Optical Receiver.*

The 90 degree hybrid mixes the optical received electrical field E_s with the field E_{LO} generated by a local oscillator (LO). The four output signals E_1, E_2, E_3, E_4 are:

$$\boldsymbol{E_1} = \frac{1}{2}(\boldsymbol{E_s} + \boldsymbol{E_{LO}}), \quad (4)$$

$$\boldsymbol{E_2} = \frac{1}{2}(\boldsymbol{E_s} - \boldsymbol{E_{LO}}), \quad (5)$$

$$\boldsymbol{E_3} = \frac{1}{2}(\boldsymbol{E_s} + \boldsymbol{jE_{LO}}), \quad (6)$$

$$\boldsymbol{E_4} = \frac{1}{2}(\boldsymbol{E_s} - \boldsymbol{jE_{LO}}), \quad (7)$$

The two output electrical signals *I(t)* and *Q(t)* (see Figure 2) are given by (Kikuchi, 2010):

$$\boldsymbol{I(t) = I_{I\_1}(t) - I_{I\_2}(t) = R\sqrt{P_s P_{LO}} cos\{\theta_{sig}(t) - \theta_{LO}(t)\}}, \quad (8)$$

$$\boldsymbol{Q(t) = I_{Q\_1}(t) - I_{Q\_2}(t) = R\sqrt{P_s P_{LO}} sin\{\theta_{sig}(t) - \theta_{LO}(t)\}}, \quad (9)$$

where P_s and P_{LO} are the power values related with the received and the LO signals respectively; R is the responsivity of the photodiodes, θ_{sig} and θ_{LO} are the phases of the transmitted and LO signals respectively.

Then, analog-to-digital converters (ADCs) digitize the electrical I and Q components for further digital signal processing. The DSP performs electronic compensation, bit detection and measurement of the quality of the signal. Backpropagation and CMA electronic compensation techniques compensate the effects of the optical fiber, and they are described next section. Bit detector estimates the transmitted bits based on the compensated I and Q components. The quality of the received signal is calculated using different performance parameters such as the Signal to Noise Ratio (SNR), EVM or Bit Error Rate (BER). We use EVM to evaluate the performance of the electronic compensation techniques.

2.2. Electronic compensation

We use two methods based in post electronic compensation to compensate the chromatic dispersion of the optical fiber: CMA and Backpropagation. In both cases we compensate only the linear effect of the optical fiber.

CMA is a blind equalization method that uses an adaptive linear filter. The cost function in CMA was proposed by Godard (Godard, 1980; Chimeno, 1996) and can be expressed as follow:

$$D^2 = E\{e(n)\} = E\{(|y(n)|^2 - 1)^2\}, \quad (10)$$

where $E\{.\}$ indicates statistical expectation, $y(n)$ is the filter output and e(n) is the error function.

The iterative equation to update the coefficients of the filter is obtained using the method of gradient descendent to minimize the cost function:

$$w(n+1) = w(n) - \frac{1}{2}\mu\nabla(E\{e^2(n)\}), \quad (11)$$

where μ is the step-size parameter and the gradient of the cost function is defined as:

$$\nabla(E\{e^2(n)\}) = 2\, y(n)\, e(n)\, x(n), \quad (12)$$

replacing (12) into (11):

$$w(n+1) = w(n) - \mu\, y(n)\, e(n)\, x(n), \quad (13)$$

where x(n) is the input signal to the filter.

On the other hand, Backpropagation uses the NLSE (Nonlinear Schrodinger Equation) to model linear and nonlinear optical fiber propagation effects (Agrawal, 2010):

$$\frac{\partial A}{\partial z} = j \sum_{k=2}^{\infty} \frac{j^k \beta_k}{k!} \frac{\partial^k A}{\partial t^k} + j\gamma |A|^2 A - \frac{\alpha}{2} A \quad (14)$$

where the first term at the right hand represents the chromatic dispersion, a linear effect, and the second term represents the Kerr effect, a nonlinear effect. A is the envelop of the electrical field, γ is the nonlinear coefficient and β_k is the dispersion coefficient of order k.

If the nonlinear effect is neglected, and considering only the second β_2 and third order β_3 dispersion coefficients, for a fiber length z, the response function of the optical fiber in the frequency domain is obtained solving (14) (He & Li, 2010):

$$H(\omega) = \exp\left(\frac{j\beta_2 \omega^2 z}{2} - \frac{j\beta_3 \omega^3 z}{6}\right) \quad (15)$$

Backpropagation uses the inverse response of the optical fiber to compensate the optical fiber impairments. It takes the received signal x(t) and calculates the output using t he following equation:

$$\boldsymbol{y(t) = F^{-1}\{\, H(\omega).\, F\{x(t)\}\,\}}, \quad (16)$$

where $F\{.\}$ and F^{-1} {.} indicates direct and inverse Fourier transform respectively.

3. Metodology

We use the simulation tools Optsym and Matlab to evaluate the performance of the algorithms CMA and Backpropagation in a NG-PON. With Optsym we simulate the optical components including the lasers, optical fiber, photodetectors and passive components. With Matlab we simulate and evaluate the electronic compensation algorithms. We compare CMA and Backpropagation calculating the EVM and the computational complexity.

3.1. Simulation setup

The optical access network has fiber lengths up to 40 km with 40 Gb/s. In the transmitter we use a CW laser at 1550 nm with transmitted power of 0 dBm. The electrical signal is provided by a pseudo-random binary sequence (PRBS) with levels of 5 and -5 V, and 32 samples per symbol. We set the V_π value to 5 V, and the insertion loss to 3 dB in the intensity optical modulators.

The model of the optical fiber considers the linear and nonlinear effects. We assume a SSMF (standard single mode fiber) with the parameters presented in Table 1.

Table 1. *Parameters of the optical fiber.*

Parameter	Value
Attenuation, α	0.20 dB/km
Second order dispersion coefficient, β_2	-21.68262 ps^2/km
Third order dispersion coefficient, β_3	0.17349 ps^3/km
Nonlinear coefficient, γ	1.19226 1/ W/km

In the receiver, the LO laser has the same parameters as the transmitter laser. Photodetectors are PIN with responsivity values equal to 0.8751 A/W. The 90 hybrib coupler and the balanced pothodetectors were configured without noise because we are evaluating the capacity of the algorithms to compensate the chromatic dispersion of the optical fiber.

The post compensation algorithms were developed in Matlab, in this case, it was necessary to do a co-simulation between Optsym and Matlab. The CMA adaptive filter uses 21 coefficients.

3.2. EVM

We use EVM to evaluate the performance of electronic compensation algorithms. The EVM value for N received symbols is calculated with the difference between the compensated (I_k,Q_k) and ideal ($\tilde{I}_k$,$\tilde{Q}_k$) symbol vectors (IEEE, 2012; Math Works, 2015):

$$EVM = \sqrt{\frac{\frac{1}{N}\sum_{k=1}^{N}\left|(I_k-\tilde{I}_k)^2+(Q_k-\tilde{Q}_k)^2\right|}{\frac{1}{N}\sum_{k=1}^{N}\left({I_k}^2+{Q_k}^2\right)}} * 100\,\% \,. \quad (17)$$

We compare the results with the EVMs within the limit permit of 17.5 % for QPSK modulation format, as required by the regulation (Kanno et al., 2014; Dat et al., 2013; RF Wireless-World, 2012).

4. Results and discussion

In this section we present simulation results comparing the performance between CMA and Backpropagation in a NG-PON. Figure 3 shows the EVM for fiber lengths between 10 and 50 km. Results show that the maximum fiber length without electronic compensation is 15 km. With CMA the maximum fiber length increases up to 33.5 km. Backpropagation presents EVM values around 0.1 % for the different fiber lengths tested in the simulations.

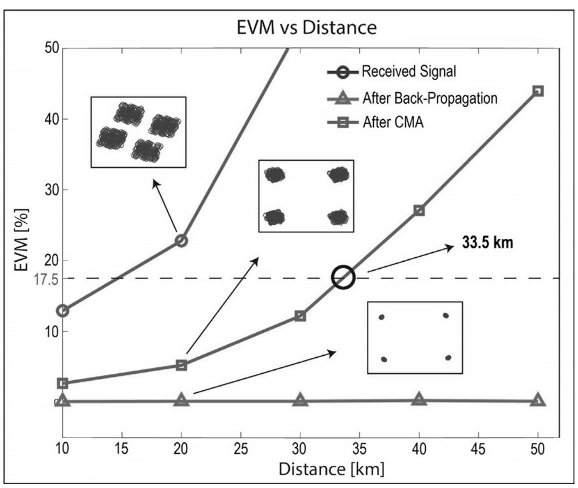

Figure 3. EVM vs Distance with and without electronic compensation at 40 Gb/s. The inset shows the eye diagram at 20 km of fiber length.

Figure 4 presents the EVM value in function of the received optical power, obtaining -140 dBm of receiver sensitivity using CMA.

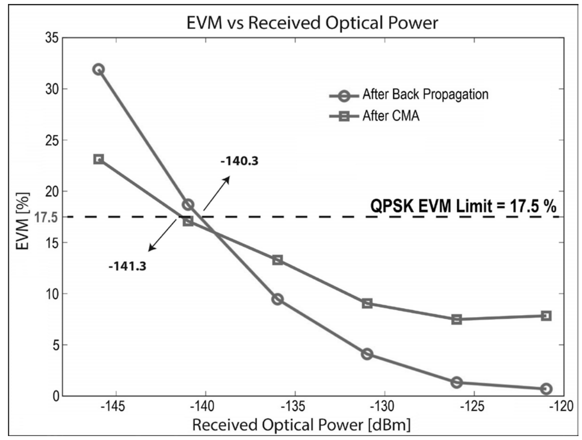

Figure 4. EVM vs Received optical power with CMA and Backpropagation at 40 Gb/s with 20 km of fiber length.

The link budget is 140 dBm with a transmitted power equal to 0 dBm. Table 2 presents typical values of an access network to calculate the maximum number of users, obtaining 129 dB of available link budget. With more realistic parameters in the receiver we would obtain a lower link budget. However, we expect a high number of users in the access using coherent modulation and the electronic compensation algorithm CMA.

Table 2. Link budget available for users using CMA.

Item	Loss [dB]
Fiber attenuation: 20 km, including fiber splices	4
Connectors and distribution boxes	4
Margin	3
Total loss	11
Available for users (link budget) – (total loss)	129

Finally, we compare the computation complexity of CMA and Backpropagation. We count the number of complex multiplications and additions considering a block with 128 samples for the FFT algorithm. CMA requires only a sample per symbol, executing equation (13) only four times to process 128 samples.

Table 3 presents the number of complex operations for Backpropagation and Table 4 for CMA, considering a blocks with 128 samples.

Table 3. *Complex operations of Backpropagation with 128 samples.*

Item	Complex multiplications	Complex additions
FFT of the input signal	448	896
Complex multiplication between the input signal and the fiber response	128	
$H(\omega)$		
Inverse FFT	448	896
Total	1024	1792

Table 4. *Complex operations of CMA with 128 samples.*

Item	Per sample		Per 128 samples	
	Complex multiplications	Complex additions	Complex multiplications	Complex additions
e(n) calculation	2	1	8	4
w(n) calculation	4	1	16	4
y(n) calculation	21	20	84	80
		Total	188	88

We can see that CMA requires less computational complexity, representing a reduction in the required clock frequency and the required amount of memory. The use of CMA in the access implies a lower cost compared with Backpropagation.

5. Conclusion

In this paper we compare the performance of Backpropagation and CMA electronic compensation techniques in a NG-PON with QPSK modulation format and coherent detection to compensate the chromatic dispersion in the optical fiber. We obtained EVM values lower than 17.5 % with fiber lengths up to 33.5 km with 40 Gb/s of data bit rate. A preliminary calculation indicates that QPSK with CMA allow a high number of users in the access. We also calculate the computational complexity, and Backpropagation requires 10 times more complex operations compared with CMA, to process blocks with 128 samples. We present the use of CMA as a viable alternative in the NG-PON to reduce the computational requirements compared with Backpropagation.

6. References

Agrawal, G. P. (2010). *Fiber-Optic Communication Systems Fourth Edition.* New York: John Wiley & Sons.

Alvarez-Guerrero, J., & Amaya-Fernandez, F.O. (2016). Impacto de los efectos lineales y no lineales en sistemas WDM-PON con formato de modulación DPSK. *Journal UIS Ingenierías* 14 (2), 35-45.

Asif, R., Lin, C. Y., & Schmauss, B. (2011). Digital Backward Propagation: A Technique to Compensate Fiber Dispersion and Non-Linear Impairments. In: C. Cuadrado-Laborde (Editor), *Applications of Digital Signal Processing*. InTech, (Chapter 2).

Carmona-Rodríguez, C., Amaya-Fernandez, F., Alvarez-Guerrero, J., & Cárdenas, A.M. (2015). Linewidth penalty on optical access networks using DPSK modulation format. *Ingenius* (13), 38-43.

Chimeno, M. F. (1996). *Obtención de micropotenciales cardíacos latido a latido por vía superficiales latido a latido por vía superficial*. Doctoral thesis, Department of Electronic Engineering, Universidad Polotécnica de Catalunya, Catalunya, España.

Cvijetic, N., Cvijetic, M., Huang, M. F., Ip, E., Huang, Y. K., & Wang, T. (2012). Terabit Optical Access Networks Based on WDM-OFDMA-PON. *Journal of Lightwave Technology* 30 (4), 493-503.

Dat, P. T., Kanno, A., & Kawanishi, T. (2013). *Performance evaluation of LTE signal transmission* *over a seamlessly integrated radio-over-fiber and millimeter-wave wireless link.* In Procedings of IEEE Globecom Workshops (GC Wkshps), Atlanta, United States, p. 748-753.

Godard, D. (1980). Self-Recovering Equalization and Carrier Tracking in Two-Dimensional Data Communication Systems. *IEEE Transactions on Communications* 28 (11), 1867-1875.

He, K., & Li, X. (2010). An Efficient Approach for Time-Domain Simulation of Pulse Propagation in Optical Fiber. *Journal of Lightwave Technology* 28 (20), 2912-2918.

Hernández, M., Arcia, A., Alvizu, R., & Huerta, M. (2012). *A review of XDMA-WDM-PON for Next Generation Optical Access Networks.* In Pro-ceedings of the 2012 Global Information Infrastructure and Networking Symposium (GIIS), Choroni, Venezuela, p. 1-6.

IEEE (Institute of Electrical and Electronics Engineers). (2004). *Local and metropolitan area networks—Part 3: CSMA/CD Access Method and Physical Layer Specifications Amendment: Media Access Control Parameters, Physical Layers, and Management Parameters for Subscriber Access Networks*. Standard for Information Technology IEEE 802.3ah. http://ieeexplore.ieee.org.

IEEE (Institute of Electrical and Electronics Engineers). (2009). *Local and metropolitan area networks—Part 3: CSMA/CD Access Method and Physical Layer Specifications Amendment 1: Physical Layer Specifications and Management Parameters for 10 Gb/s Passive Optical Networks.* Standard for Information Technology IEEE 802.3av. http://ieeexplore.ieee.org.

IEEE (Institute of Electrical and Electronics Engineers). (2012). IEEE 802.16.1-2012: WirelessMAN-*Advanced Air Interface for Broadband Wireless Access Systems.* http://ieeexplore.ieee.org.

ITU (International Telecommunication Union). (2008). *Gigabit-capable passive optical networks (GPON): General characteristics.* Recomendación ITU-T G.984.1. https://www.itu.int.

ITU (International Telecommunication Union). (2012). *10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms*. Recommendation ITU-T G.987. https://www.itu.int

Kanno, A., Dat, P. T., Hosako, I., Kawanishi, T., & Ogawa, H. (2014). *Radio-on-terahertz over fiber system for future mobile fronthauling.* In Proceedings of the Global Communications Conference (GLOBECOM), Austin, United States, p. 2218-2222.

Kataoka, N., Cincotti, G., Wada, N., & Kitayama, K. (2011). *Demonstration of asynchronous, 40Gbps x 4-user DPSK-OCDMA transmission using a multi-port encoder/decoder*. In Proceedings of 37th European Conference and Exhibition on Optical Communication. Ginebra, Suiza, p. 1-3.

Kikuchi, K. (2010). Coherent Optical Communications: Historical Perspectives and Future Directions. In: *High Spectral Density Optical Communication Technologies*, Springer Berlin Heidelberg, (Chapter 2).

Kim, S. Y. (2010). *Single and multi-carrier coherent detection using DSP technologies for future optical access systems*. In Proceedings of the 9th International Conference on Optical Internet (COIN). Jeju, South Korea, p. 1-3.

Latal, J., Vitasek, J., Koudelka, P., Siska, P., Poboril, R., Hajek, L., Vanderka, A., & Vasinek, V. (2014). *Simulation of modulation formats for optical access network based on WDM-PON*. In Proceedings of the 16th International Conference on Transparent Optical Networks (ICTON). Graz, Austria, p. 1-7.

Lavery, D., Thomsen, B. C., Bayvel, P., & Savory, S. J. (2015). Reduced complexity equalization for coherent long-reach passive optical networks [invited]. *IEEE/OSA Journal of Optical Communications and Networking* 7 (1), A16-A27.

Lin, R. (2008). *Next Generation PON in Emerging Networks.* In Proceedings of the Optical Fiber communication/National Fiber Optic Engineers Conference (OFC/NFOEC). San Diego, United States, p. 1-3.

Ling, C., Dahlfort, S., & Hood, D. (2010). *Evolution of PON: 10G-PON and WDM-PON.* In Procedings of the Asia Communications and Photonics Conference and Exhibition (ACP). Shanghai, China, p. 709-711.

Maeda, W., Abe, J., Noguchi, H., & Fukuchi, K. (2014). *Optical-Electrical Hybrid Backpropagation for Hardware-efficient Digital Coherent Receiver with Nonlinear Compensation*. In Proceedings of the OptoElectronics and Communication Conference and Australian Conference on Optical Fibre Technology (OECC/ACOFT). Melbourne, Australia, p. 899-900.

MathWorks, (2015). *EVM Measurement.* http://www.mathworks.com/.

Morosi, J., Hoxha, J., Martelli, P., Parolari, P., Cincotti, G., Shimizu, S., Wada, N., & Boffi, P. (2016). 25 Gbit/s per user coherent all-optical ofdm for tbit/s-capable PONs. *IEEE/OSA Journal of Optical Communications and Networking* 8 (4), 190-195.

Muciaccia, T., Gargano, F., & Passaro, V. M. (2014). Passive Optical Access Networks: State of the Art and Future Evolution. *Photonics* 1 (4), 323-346.

Napoli, A., Maalej, Z., Sleiffer, V. A., Kuschnerov, M., Rafique, D., Timmers, E., Spinnler, B., Rahman, T., Coelho, L. D., & Hanik, N. (2014). Reduced Complexity Digital Back-Propagation Methods for Optical Communication Systems. *Journal of Lightwave Technology* 32 (7), 1351-1362.

Neto, L. A., Chanclou, P., Charbonnier, B., Genay, N., Saliou, F., Xia, R., Ouzzif, M., Aupetit-Berthelemot, C., Masson, J. L., Grard, E., & Rodrigues, V. (2011). *Up to 40Gb/s optically amplified AMOOFDM for next generation PON networks*. In Proceedings of the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC). Los Angeles, United States, p. 1-3.

Pellicer, S., Santa, G., Bleda, A L., Maestre, R., Jara, A. J., & Skarmeta, A. G. (2013). *A Global Perspective of Smart Cities: A Survey*. In Proceedings of the 7th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing. Taichung, China, p. 439-444.

Poirier, M., Boudreau, M., Lin, Y. M., Narayan, R., Chen, C., Hong, X., Olson, R., Liu, X., Gokhale, M., Young Ma, J., & Eshelman, M. (2015). *InP integrated coherent transmitter for 100 Gb/s DP-QPSK transmission*. In Proceedings of the Optical Fiber Communications Conference and Exhibition (OFC). Los Angeles, United States, p.1-3.

Reis, J. D., Neves, D. M., & Teixeira, A. L. (2011). *Transmission aspects on broadband coherent optical access networks*. In Proceedings of the 3rd Latin-American Conference on Communications (LATINCOM). Belem do Para, Brasil, p. 1-6.

RF Wireless-World, (2012). *LTE UE RF Conformance testing and Measurements*. http://www.rfwireless-world.com/Tutorials/LTE-UE-testing-measurements.html.

Seimetz, M. (2009). *High-Order Modulation for Optical Fiber Transmission*. Berlin Heidelberg: Springer.

Shim, H. K., Cho, K. Y., Hong, U. H., & Chung, Y. C. (2013), *Demonstration of 40-Gb/s QPSK upstream transmission in long-reach RSOA-based coherent WDM PON using offset PDM technique*. In Proceedings of the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC). Anaheim, United States, p. 1-3.

Sotiropoulos, N., & de Waardt, H. (2013). Advanced Differential Modulation Formats for Optical Access Networks. *Journal of Lightwave Technology* 31 (17), 2829-2843.

Synopsys Group Optical Solutions (2013). *OptSim Models Reference Volumen I Sample Mode*. http://www.academia.edu.

ITU-FG-SSC (International Telecommunication Union – Focus Group – Smart Sustainable Cities). (2014). *An overview of smart sustainable cities* *and the role of information and communication technologies*. http://www.itu.int.

Zhang, Z., Chen, X., Wang, L., & Zhang, M. (2013). *40-Gb/s QPSK downstream and 10-Gb/s RSOA-based upstream transmission in long-reach WDM PON employing remotely pumped EDFA and FBG optical equalizer.* In Proceedings of the 8th International ICST Conference on Communications and Networking in China (CHINACOM). Guilin, China, p. 788-791.