

Performance of Back-propagation and Self Organizing Map Neural Equalizers for Asymmetrically Clipped Optical OFDM

*Farideh Javidi, and **Hossein Khoshbin

Engineering Department,
Ferdowsi university of Mashhad,
Mashhad, Iran

*Faride.javidiniroumand@stu-mail.um.ac.ir

**Khoshbin@um.ac.ir

Abstract— This paper evaluates the performance of back-propagation (BP) and self organizing map (SOM) equalizer for indoor asymmetrically clipped optical OFDM (ACO-OFDM) wireless systems. Although in OFDM, parallel transmission and cyclic prefix addition improve the communication efficiency, there is still performance degradation due to inter-symbol interference (ISI) in dispersive channels. Simulation results indicate that BP multilayer perceptron and SOM neural equalizers enhance the bit error rate performance of ACO-OFDM systems in diffused channels for high signal to noise ratio. Moreover, proposed BP and SOM equalization require only 0.05 and 0.005 percent of ACO-OFDM symbols for training in a sec respectively while in single-tap equalization channel state information is necessary at the receiver.

I. INTRODUCTION

Nowadays bandwidth requirement per user is highly increasing, and bandwidth congestion in radio frequency systems has led to utilizing optical networks. Optical wireless communicating systems provide not only huge bandwidth, but also wide range of mobility per user. Outdoor optical wireless communication which is called free space optical (FSO) is a well-known application of optical wireless communication. These days, FSO has a rapid industrial growth [1]. On the other hand, indoor optical wireless communication is the other type of optical wireless application which utilizes optical wireless media for transmitting data in places which are limited with walls and ceiling. Indoor optical wireless communications provide immune links in large places as well as huge bandwidth and wide range of mobility. Furthermore, indoor optical wireless communicating systems are preferable in the locations with electromagnetic interference such as subways rather than the radio frequency communicating.

There are different topologies for transmitting in indoor optical wireless systems. Line-of-sight links provide high data rates, but at the cost of high blocking probability and narrow range of user mobility [2]. In diffused links not only there is no blocking, but also wide range of user mobility is provided. In fact, diffused links depend on the reflection of the light from opaque surfaces such as walls and ceilings [3]. So, multipath is the dominant phenomena of dispersive channels in indoor optical wireless systems and data rate reduces considerably, since of rising inter-symbol interference (ISI). However, as the channel becomes more dispersive, the higher penalty of ISI should be paid [4].

There are several techniques to mitigate ISI of dispersive channels in indoor optical wireless systems. Utilizing particular transceivers [2] and applying optical impulse response modulation [3] are cited as combating ISI techniques in indoor optical wireless systems as well as different equalization techniques. These techniques for common modulation; on-off keying and pulse position modulation, are including the maximum likelihood sequence detection (MLSD) technique [4], adaptive equalizers [5,6] and artificial neural network (ANN) based equalizers [5]-[6].

In references [10]-[14], optical orthogonal frequency division multiplexing (OFDM) is applied for combating ISI in dispersive channels. The key feature in the OFDM communicating is that data transmit in parallel on a number of subcarriers of different orthogonal frequencies [11]. Due to parallel transmission, every OFDM symbol became longer. Furthermore, cyclic prefix have an important role to exceed the length of symbols. Hence, the effects of ISI reduce noticeably and OFDM communication became resistant to ISI.

In optical wireless systems, optical beams of light are used to transmit information. So, time domain optical OFDM signals should be non-negative. For this purpose, in DC optical OFDM (DCO-OFDM) method a large DC bias is added to the signal. In another method, negative part of signal is clipped. In this approach which is called asymmetrically clipped optical OFDM (ACO-OFDM), data modulation is done specifically where there is no data missing by clipping [11].

Although parallel transmission in OFDM communication is noticeably combating ISI, there are still some negative effects. In ACO-OFDM systems, single-tap equalization is the only approach of equalization which is applied for each frequency subcarrier and consists of a gain and a delay. In this paper two types of ANN based equalizers have been proposed for mitigating ISI of dispersive channels in indoor optical wireless systems with ACO-OFDM modulation. Indoor optical wireless systems with dispersive channel and ACO-OFDM modulation is described in detail in Section 2. In Section 3, equalization methods for combating ISI are presented. Back-propagation (BP) neural equalizer and self organizing map (SOM) neural equalizer are introduced in Section 4 for the special case of ACO-OFDM systems. In Section 5, simulation results of proposed BP and SOM neural equalizers are discussed and a concise comparison of their performance is presented. Finally, conclusion remarks are given in Section 6.

II. SYSTEM DESCRIPTION

A. Indoor Optical Wireless System Model

Optical wireless communication system is a wireless system in which signals are transmitted through an optical channel. The most common modulation in optical channels is Intensity Modulation (IM) where at the receiver Direct Detection (DD) technique is used via a photodetector. In IM, data are modulated with instantaneous intensity of an optical signal. At the receiver, the optical signal is converted to electrical one through DD and data would be extracted. The schematic of an optical wireless system is shown in Fig. 1 while $x(t)$ represents the instantaneous optical power which carries data, $n(t)$ is the noise signal which is independent of $x(t)$ and generally modelled as additive white Gaussian noise signal, and $y(t)$ is the detected signal at the receiver.

The channel model in Intensity Modulation/Direct Detection technique is derived as follows:

$$y(t) = R \cdot x(t) * h(t) + n(t) \quad (1)$$

where R is the photodetector responsivity, $*$ is continuous-time convolution, $h(t)$ is the optical channel impulse response which is normalized via (2).

$$\sum_{k=0}^{\infty} h(kT) = 1 \quad (2)$$

where T is the sampling time.

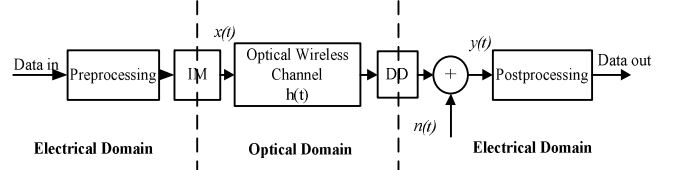


Figure1. Schematic of Optical Wireless System

Dispersive channels in indoor optical wireless systems are usually modelled as low-pass filters [3]. To be more precise, the ceiling bounce model is defined whose impulse response is the most widely used due to its computational efficiency and an excellent matching with measured channels. Following [5-9] the channel impulse response of ceiling bounce model is described as:

$$h_c(t, a) = \frac{6a^6}{(t+a)^7} u(t) \quad (3)$$

where a is calculated via (4) and $u(t)$ is a unit step function.

$$a = \frac{2H}{c} \quad (4)$$

where H is the height of the ceiling above the transceivers and c is the light velocity.

The dispersion of the diffused channels are represented by the time delay that the channel spread the input signal. The delay spread factor of a dispersive channel is given by:

$$D_{rms} = \frac{a}{12} \sqrt{\frac{13}{11}} \quad (5)$$

B. Asymmetrically Clipped Optical OFDM

Parallel transmission and adding cyclic prefix make the OFDM communication compatible for diffused channels in indoor optical wireless communicating. ACO-OFDM signalling is widely in use, since it requires lower optical power rather than DCO-OFDM scheme. However, in ACO-OFDM only odd frequency subcarriers are modulated and as a result its bandwidth is half of the DCO-OFDM. All in all, in this paper ACO-OFDM is selected to study.

For constructing an ACO-OFDM frame just like other OFDM schemes after serial to parallel the inverse fast Fourier transform is used to conveying the signal in time domain. Since, IM is utilized in optical wireless systems, the time domain signal must be real. Therefore, the size of IFFT is obtained with $2N$ points, and only $N/2$ carry data; because only odd frequency subcarriers carry data. Fig. 2 shows zero padding in ACO-OFDM frame structure.

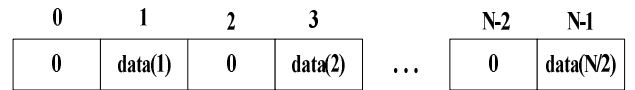


Figure2. ACO-OFDM frame structure

ACO-OFDM is a promising modulation in indoor optical wireless systems due to its remarkable resilience in respect to ISI of dispersive channels. Performance of the ACO-OFDM signalling in comparison to the other common modulation has been studied in [11-14]. It is illustrated that while ACO-OFDM requires the same bandwidth as OOK signals, its performance in electrical domain is as same as OOK systems. In other words, electrical signal to noise ratio requirement for the ACO-OFDM systems is as same as the OOK systems. While for changing the electrical SNR to optical one, ACO-OFDM requires much less. Therefore, ACO-OFDM systems require less optical power to achieving the same bit error rate performance as the OOK systems, though signals in both systems are transmitted with similar bandwidth. However, channel state information is necessary at the receiver because of single-tap equalization in the optical OFDM systems. Reference [13] indicates that when channel information is unavailable at the receiver; OOK significantly outperforms ACO-OFDM at the cost of three times more computational complexity and faster analog-to-digital converters and higher oversampling ratios.

III. EQUALIZATION

The common technique for compensating ISI in diffused channels is equalization. Equalization technique is applied to a communication system by incorporating an equalizer at the receiver to minimize the effect of ISI in a dispersive channel. Basically, an equalizer is a finite impulse response filter which its frequency response is the inverse of the channel frequency response. However, channel frequency response is usually unknown in advanced and might be time varying such as in indoor optical wireless systems. In this case, adaptive equalization is the preferred option, where channel frequency response is estimated at the receiver by transmitting several training signals.

Channel equalization can be considered as a classification problem [16]. Since, the optimal solution for this classification issue is inherently nonlinear; the nonlinear structure of artificial neural network enhances the performance of equalization [16]. The functional unit of ANN is a neuron which is shown in Fig. 3.

Each neuron has a simple functionality which is implied in (6).

$$y_j = f \left(b + \sum_{i=1}^n w_{ij} x_i \right) \quad (6)$$

where b is the input bias, x_1, \dots, x_n are the neuron inputs, w_{1j}, \dots, w_{nj} are the weights, y_j is the neuron output, and $f(\cdot)$ is the activation function. The sigmoid function and linear function are the common activation functions used in the ANN for the classification purpose such as in equalizers [16]. However, competitive function is the other type of activation function which is recently used in the ANN based equalizers [17,18].

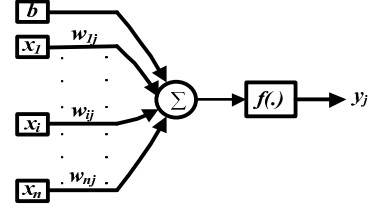


Figure3. Neuron Structure

Network architecture is the neuron arrangement in the ANN. Each ANN based equalizer consists of an input layer and an output layer. Number of neurons in input layer depends on the order of the equalizer while this number in output layer differs due to the communication application. In some cases, the ANN equalizer may have additional hidden layer which consists of some neurons [16].

IV. PROPOSED ANN BASED EQUALIZER

In this paper, two ANN based equalizers are proposed for compensating the negative effect of ISI in dispersive channels for ACO-OFDM communication systems. The neural equalization is applied in frequency domain part of ACO-OFDM signal where ACO-OFDM frame is demapped. In fact, M level QAM symbols are equalized in this approach.

A. Back-propagation Neural Equalizer

Back-propagation (BP) algorithm is one of the most common learning algorithms used in neural networks for equalizing purpose. This algorithm works on a multi-layer perceptron which is a kind of neural networks with several hidden layers. BP algorithm achieves to the global minimization by steepest descent method [19]. Although the traditional BP algorithm works in real domain, signals to be equalized in radio frequency OFDM systems are complex. Therefore, in radio frequency OFDM equalization studies, the algorithm has been extended to the complex domain [19,20].

This paper presents another technique which is applied to equalize the complex-valued M-QAM symbols of ACO-OFDM signals in indoor optical wireless systems with BP neural equalizer. In this technique, the real and complex parts of the ACO-OFDM signal are discriminated and are applied to the neural equalizer. The BP neural equalizer inputs include the values of the real part and the imaginary part of the complex-valued QAM symbols of ACO-OFDM signal separately in this technique. As a consequence the inputs of neural equalizer have real values and the equalizer operates in real domain. Since each ACO-OFDM frame carries P bit data for equalizing, number of input neurons are 2.P for real and imaginary parts of input signal. In this paper, as it is indicated in Fig. 4, the BP neural equalizer architect is 2.P input neurons, a hidden layer with several neurons and an output layer which consists of 2.P neurons that represents the real and imaginary parts of the equalized M-QAM symbols of ACO-OFDM signal.

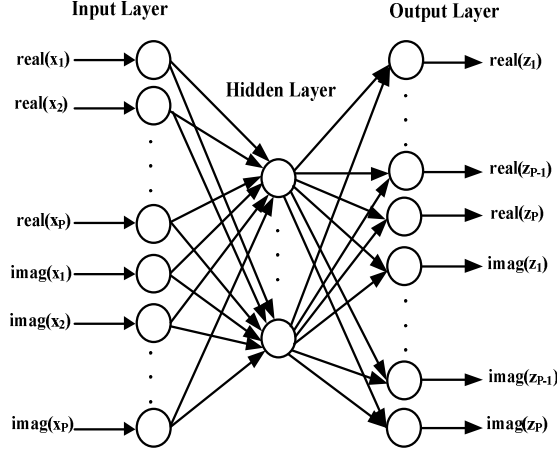


Figure 4. Proposed BP neural equalizer architecture

B. Self-Organizing Map Neural Equalizer

Self-organizing map (SOM) neural networks are a kind of competitive neural networks. In SOM networks such as competitive ones, the network clusters the inputs into groups. But, clustering in SOM is trained and is able to be affected by target outputs. The SOM network learns to classify inputs according to how they are arranged in the input space [21]. In indoor optical wireless communication systems there are M levels that the equalizer categorizes M-QAM symbols into them by applying ACO-OFDM signalling.

In this approach of equalizing, again there is a problem which relates to real functionality of SOM neural networks. To solve this problem, the real and imaginary parts of the QAM symbols of ACO-OFDM signal has been separated and applied to a real SOM equalizer.

In this paper, 4-QAM is used as a pre-modulation for ACO-OFDM signalling in dispersive channels for indoor optical wireless systems. It is assumed that the real and imaginary parts of each QAM symbols indicate the position of them in the complex plane. Fig. 5 shows the position of QAM symbols in an ACO-OFDM frame after sending through a dispersive channel. As it is seen the channel outspreads the QAM symbols while before transmitting, they have been clustered into 4 groups of $\{1+j1, -1+j1, 1-j1, -1-j1\}$.

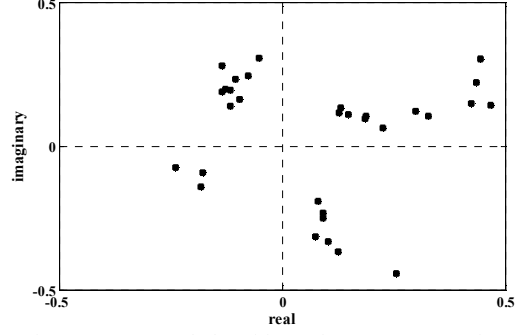


Figure 5. QAM symbol positions of an ACO-OFDM frame

So, by incorporating an equalizer at the receiver, displaced symbols would be clustered and shifted to the right position.

V. SIMULATION RESULTS AND DISCUSSION

The block diagram of an ACO-OFDM system for evaluating the performance of the proposed equalizers is shown in Fig. 6.

As it is seen in Fig. 6, at first the generated data are arranged in 4-QAM constellation and frame mapping is implemented as it is explained in Section 2. Then reverse complex conjugate is inserted to have a real valued time domain OFDM signal. After applying IFFT with $2N$ points, cyclic prefix is added in time domain to combat ISI in dispersive channels. After parallel to serial reshaping, negative part of OFDM signal will be clipped to satisfy the non-negativity constraint of optical systems. It is theoretically shown that in ACO-OFDM signalling, clipping the negative part of the signal would not distort the information [11].

In optical domain after IM, the signal is transmitted through dispersive optical wireless channel with impulse response of $h(t)$ which is normalized via (2). The dispersion of the diffused channel is considered as 5 nsec. At the receiver after DD the electrical noise, $(n(t))$; is added which is considered as additive white Gaussian with double sided spectral density of $N_0/2$.

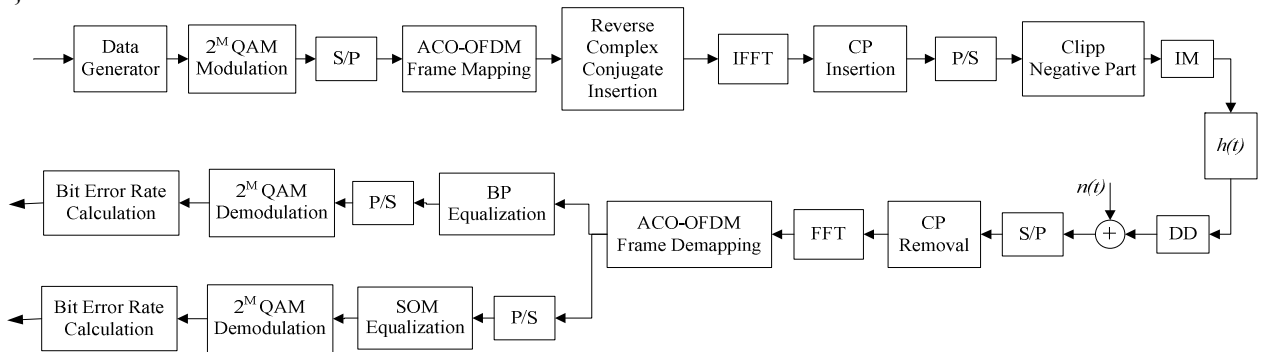


Figure 6. ACO-OFDM block diagram for simulation

Specific parameters of ACO-OFDM transmitting for the sample indoor optical wireless system are shown in Table I.

In Table I, length of the ACO-OFDM symbol, (L); specified the sample rate of the system. In this case, it is assumed that the sample rate is 160 Msample/sec which provides maximum data rate of 62 Mbps.

At the receiver shown in Fig. 6 firstly serial to parallel conversion is executed. After removing the cyclic prefix, FFT is applied with $2.N$ points. At frequency domain, 4-QAM symbols are extracted from ACO-OFDM frame and fed to the proposed neural equalizers; back-propagation multilayer perceptron and self organizing map neural equalizer. Table II and III illustrate the special parameters of proposed BP and SOM neural equalizers for simulation, respectively. At the end, data will be extracted from equalized QAM symbols.

In order to verify the performance of proposed equalizers, Fig. 7 shows BER performance of applied systems as a function of electrical signal to noise ratio in a dispersive channel with Drms 5 nsec. Following [5-9] electrical SNR is defined as:

$$SNR_{elec} = \frac{R^2 P^2}{2R_b N_0} \quad (7)$$

where R is the photodetector responsivity, P is the average optical power, R_b is the bit rate and N_0 is the one sided noise spectral density.

Table I: Simulation parameters of sample indoor optical wireless system with ACO-OFDM modulation

Parameters	Symbol	value
Photodetector responsivity	R	0.5
Size of QAM Pre-modulation	M	2
ACO-OFDM symbol length	L	160
Size of FFT/IFFT	$2.N$	128

Table II: simulation parameters of BP neural equalizer

Parameters	Value
Training sequence length	500
No. of input neurons	62
No. of hidden neurons	65
No. of output neurons	62
Activation functions	Tangent-sigmoid , linear
Training algorithm	Scaled conjugate gradient back-propagation
Performance function	Mean square error

Table III: simulation parameters of SOM neural equalizer

Parameters	Value
Training sequence length	47
Topology function	2-by-2 Hexagonal pattern

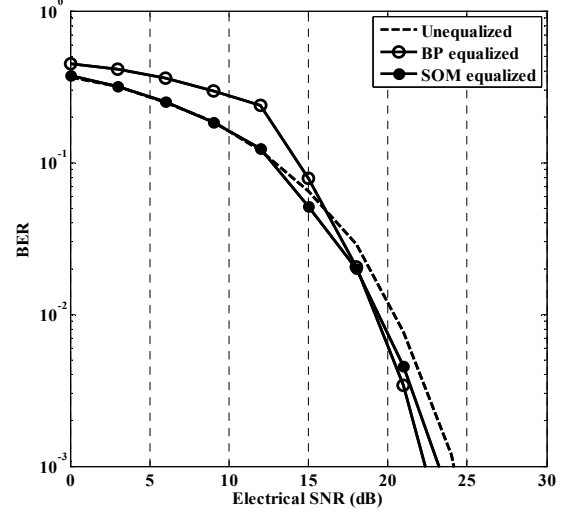


Figure7. BER performance of unequalized, BP equalized and SOM equalized ACO-OFDM system

As it is illustrated in Fig. 7, both equalizers improve the performance of sample indoor optical wireless system with ACO-OFDM signalling in high SNRs. To be more precise, BP equalizer outperforms the SOM one in high SNRs while in low SNRs the SOM equalized system has lower BER.

Fig. 8 shows the performance of the BP neural equalizer to equalize the 4-QAM symbols at the specified electrical SNR of 25dB. As it is seen, the BP equalizer modifies the position of 4-QAM symbols in the complex plane.

Fig. 9 illustrates the clustering performance of SOM neural equalizer at two different SNRs of 15 and 25 dB. It is obvious that at higher SNR QAM symbols placed much more apart from each other and clustering is executed more efficient. Therefore, as it is shown in Fig. 7 at low SNRs, SOM equalized system and unequalized one perform similarly. But as SNR becomes higher, SOM equalized system outperforms unequalized one noticeably.

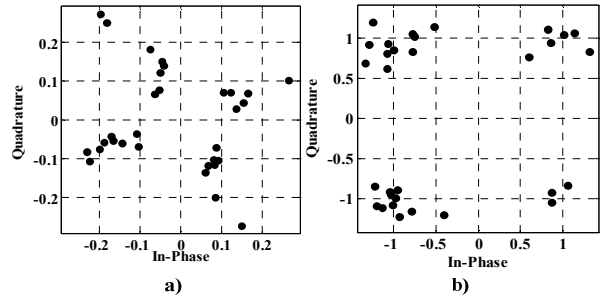


Figure8. 4-QAM symbol positions of an ACO-OFDM frame a) before equalization and b) after BP equalization

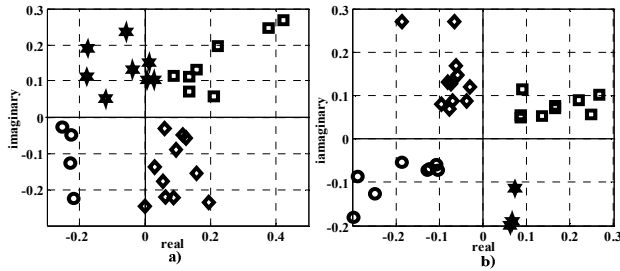


Figure9. Clustering unequaledized 4-QAM symbols of an ACO-OFDM with SOM neural equalizer at SNRs of a) 15 dB and b) 25 dB

Optical wireless channels have a slowly time-varying nature [10]. Owing to this fact, assume that the impulse response of the channel varies every second. According to Table II, BP equalizer requires 0.05% of ACO-OFDM symbols in a second for training while SOM equalizer requires only 0.005% of ACO-OFDM symbols for training as for Table III. So, BP and SOM equalization are able to equalize the partly known channel while single-tap equalization requires channel state information at the receiver.

VI. CONCLUSION

This paper proposed two ANN based equalizers for mitigating ISI in ACO-OFDM systems; back-propagation multilayer perceptron and self organizing map neural equalizer. Simulation results illustrated that both BP and SOM neural equalizers improve the BER performance of ACO-OFDM system in high SNRs. BP and SOM neural equalizers provide equalization for partly known channels, while single-tap equalizers demand for channel state information at the receiver. In a comparison between BP and SOM equalized ACO-OFDM systems, it is noteworthy to say that BP equalized system outperforms SOM equalized one in high SNRs while in low SNRs SOM equalized system has better BER performance. Moreover, the length of training sequence for SOM neural equalizer is 10 times fewer than BP one.

REFERENCES

- [1] [Online]. Available: <http://www.fsona.com>.
- [2] R. J. Green, H. Joshi, M. D. Higgins and M. S. Leeson, "Recent developments in indoor optical wireless systems," *Journal of IET communication*, vol. 2, no. 1, pp. 3-10, 2008.
- [3] M. D. A. Mohamed, S. Hranilovic, "Optical impulse modulation for indoor diffuse wireless communications," *IEEE transactions on communications*, vol. 57, no. 2, pp. 499-508, Feb. 2009.
- [4] J. G. Proakis, *Digital communications*, Third ed. New York: McGraw-Hill, Inc., 1995.
- [5] Z. Ghassemlooy and S. Rajbhandari, "Performance of diffused indoor optical wireless links employing neural and adaptive linear equalizers," presented at 6th international conference on information, communications and signal processing, Singapore, 2007.
- [6] S. Rajbhandari, Z. Ghassemlooy, "Effective denoising and adaptive equalization of indoor optical wireless channel with artificial light using the discrete wavelet transform and artificial neural network," *Journal of Lightwave technology*, vol. 27, no. 20, pp. 4493-4501, Oct. 15, 2009.
- [7] S. Rajbhandari, Z. Ghassemlooy and M. Angelova, "Wavelet-artificial neural network receiver for indoor optical wireless communications," *Journal of lightwave technology*, vol. 29, no. 17, pp. 2651-2659, 2011.
- [8] S. Rajbhandari, Z. Ghassemlooy, M. Angelova, "Bit error performance of diffuse indoor optical wireless channel pulse position modulation system employing artificial neural networks for channel equalization," published in *IET Optoelectron*, vol. 3, issue 4, pp. 169-179, 2009.
- [9] S. Rajbhandari, Z. Ghassemlooy and M. Angelova, "The performance of PPM using neural network and symbol decoding for diffused indoor optical wireless links," presented at 9th international conference on transparent optical networks, Rome, Italy, 2007.
- [10] O. Gonzalez, R. Perez-Jimenez, S. Rodrigues, J. Rabadan and A. Ayala, "OFDM over indoor wireless optical channel," published in *IEE Proc.-Optoelectron.*, Vol. 152, No. 4, pp. 199-204, 2005.
- [11] J. Armstrong, B. J. C. Schmidt, D. Karla, H. A. Suraweera and A. J. Lowery, "Performance of asymmetrically clipped optical OFDM in AWGN for an intensity modulated direct detection system," presented at global telecommunications conference, San Francisco, 2006.
- [12] S. Tian, K. Panta, H. A. Suraweera, B. J. C. Schimt, S. McLaughlin and J. Armstrong, "A novel timing synchronization method for ACO-OFDM-based optical wireless communications," *IEEE transactions on wireless communications*, Vol. 7, No.12, pp. 4958-4967, 2008.
- [13] D. J. F. Barros, S. K. Wilson and J. M. Kahn, "Comparison of orthogonal frequency-division multiplexing and pulse-amplitude modulation in indoor optical wireless links," *IEEE transactions on communications*, Vol. 60, No. 1, pp. 153-163, 2012.
- [14] J. Armstrong and J. C. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE communications letters*, Vol. 12, No. 5, pp. 343-345, 2008.
- [15] S. K. Hashemi, Z. Ghassemlooy, L. Chao and D. Benhaddou, "Channel estimation for indoor diffuse optical OFDM wireless communications," presented at 5th international conference on broadband communications, networks and systems, London, UK, 2008.
- [16] Hanzo, L., Wong, C.H. and Yee, M.S., *Adaptive Wireless Transceivers: Turbo-Coded, Turbo-Equalised and Space-Time Coded TDMA, CDMA and OFDM Systems*, John Wiley and Sons Ltd, 2002.
- [17] M. Raugi and M. Tucci, "Power-line communications channel estimation and tracking by a competitive neural network," *IEEE transactions on consumer electronics*, Vol. 52, No. 4, pp. 1213-1219, 2006.
- [18] M. Tucci, M. Raugi, A. Musolino and S. Barmada, "Blind channel estimation for power-line communications by a kohonen neural network," presented at IEEE interbational symposium on power line communications and its applications, Pisa, Italy, 2007.
- [19] E. Chen, R. Tao and X. Zhao, "Channel equalization for OFDM system based on the BP neural network," presented at 8th international conference on signal processing, Beijing, China, 2006.
- [20] M. M. A. Moustafa and S. H. A. El-Ramly, "Channel estimation and equalization using back-propagation neural networks in OFDM systems," presented at IFIP international conference on wireless and optical communications networks, Cairo, Egypt, 2009.
- [21] H. Demuth, M. Beale, M. Hagan, "Neural network toolbox user's guide," the mathworks, Inc., 1992-2009.