Investigation of Coded WOFDM System over Multimode Optical Channels

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Abstract—In this paper, the performance of Asymmetrically Clipped Optical Wavelet based Orthogonal Frequency Division Multiplexing (ACO WOFDM) system is compared to the performance of Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing (ACO OFDM) system. Then a Coded ACO WOFDM (CACO WOFDM) communication system over a multimode optical channel is investigated. The used wavelet transform is the Wavelet Packet Transform (WPT). Quadrature Amplitude Modulation (QAM) is used as the modulation format. The simulation results show a considerable performance improvement of ACO WOFDM system in terms of BER and slight performance improvement of ACO WOFDM system in terms of OSNR Compared to the ACO OFDM system. Also, from the simulation results, we find that the CACO WOFDM considerably improves the BER and OSNR performance of the communication system.

Index Terms—ACO WOFDM, ACO OFDM, CACO OFDM, Hamming code, Haar, Symlets, WPT

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation scheme simultaneously transmits many low-rate symbols on the amplitudes of orthogonal subcarriers. In conventional OFDM, the inverse Fourier transform is used to modulate low-rate symbols on the amplitudes of complex exponential subcarriers. Demodulation is performed by Fourier Transform using rectangular windowing. This process generates windowed complex exponentials that each have sinc shapes with considerable side lobes in the frequency domain. This causes Inter Carrier Interference (ICI) [1]. Advantages of wavelet transform over Fourier transform is the main motivation toward using Wavelet based OFDM (WOFDM) [2]-[6]. In WOFDM, subcarriers are the scaled and shifted versions of wavelets. Wavelets are designed in such a way to have finite length in both time and frequency domain. Wavelets have pulse shaping nature, so spectrums of wavelets contain lower side lobes than OFDM. Wavelet Packet Transform based OFDM (WPT OFDM) is a class of WOFDM [3]. WPT OFDM uses inverse WPT to modulate parallel symbols on the amplitudes of orthogonal subcarriers that are shifted and scaled versions of the mother wavelet. The WPT is used for demodulation process.

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To implement OFDM/WOFDM in optical domain, the bipolar electrical signal should be modulated on the unipolar light signal. To this end, Asymmetrically Clipped Optical (ACO) and Direct Current Optical (DCO) structures have been proposed to modulate the electrical signal on the intensity of light while Coherent detection Optical (CO) and Direct Detection Optical (DDO) structures have been offered to modulate the electrical signal on the field of light [7]-[10]. In this paper, we focus on the intensity modulation. In DCO structure, a large DC bias is added to the bipolar electrical signal to produce the unipolar electrical signal. This signal will be modulated on the intensity of light [7]-[8]. This is an inefficient process due to the high power of the obtained optical signal. ACO structure has been proposed to tackle this problem. In other words, a power efficient optical signal can be derived by clipping the bipolar electrical signal at the zero level and modulating it on the intensity of light [9]-[12].

On the other hand, channel coding is an essential component of a well-designed digital communication system. Channel coding is employed to minimize errors in digital communication systems. Repetition code reduces system errors at the cost of reducing the system information rate. It is possible to minimize the system errors without changing information rate [13]. Shannon shows that grouping data bits provides the opportunity to design such channel coding algorithms [14]. The main idea behind the Shannon's work is the vector representation of codes. Vector representation of codes is the basis of the most channel coding algorithms. In other words, mathematical representation of a code by using a generator matrix is equivalent to vector representation of the code, i.e., each codeword is represented as a linear combination of all unit vectors. However, channel coding in the OFDM structure can also has an important advantage. Coding in OFDM split the information over the large number of carriers. In other words, the signal is conditioned to ensure that modulated symbols will be much longer than the maximum delay spread introduced by the channel [15].

The coded OFDM overcomes the delay spread, but the side lobes and ICI exist as a drawback. Therefore In the current work, Hamming codes are proposed to increase the reliability of the ACO-WOFDM over the optical communication system. Hamming codes were discovered by Richard Hamming in 1950. Hamming codes are a special case of linear codes. A Hamming code can detect up to two error bits and to correct one error bit [16]-[18].

In this article, we survey the transmission performance of the ACO WOFDM system over a multimode optical channel based on Haar and Symlets wavelets [19]. Then, we investigate the performance of the Hamming coded ACO WPT-OFDM system over a multimode optical channel. The simulated system is employed for data transmission over a multimode optical link.

II. ACO WOFDM

Multipath The main advantage of OFDM is its robustness against channel dispersion. In conventional OFDM, the Fourier transform, i.e. the Inverse Discrete Fourier Transform (IDFT), is employed to modulate long duration symbols on the amplitude of the orthogonal subcarriers, i.e., complex exponentials. The obtained OFDM signal is a complex time domain signal. A real time domain signal is achieved by using an IQ modulator.

The block diagrams of an OFDM transmitter and an OFDM receiver are shown in Fig. 1 and Fig. 2, respectively. At the transmitter, a parallel to serial convertor is employed to generate parallel data. Next, each parallel data channel is mapped onto the corresponding information symbol. The information symbols are then transformed into a complex time domain samples via an IDFT. Guard Interval (GI) insertion is performed. GI acts as a space between successive OFDM symbols and therefore prevents Inter Symbol Interference (ISI). A real time passband OFDM signal is obtained through a DAC and an IQ modulator. Receiver performs the reverse operations of the transmission scheme to recover the original data.

In ACO OFDM, the bipolar OFDM signal is clipped at the zero level before being modulated on the intensity of light. If the odd frequency OFDM subcarriers are non-zero at the IDFT input, all of the clipping noise falls on the even subcarriers; the data carrying odd subcarriers are not impaired [8].

The principle of WOFDM, i.e. WPT based OFDM, is very similar to the principle of conventional OFDM, i.e. Fourier transform based OFDM. OFDM utilizes Fourier transform to perform modulation and demodulation processes while WOFDM utilizes WPT to implement modulation and demodulation. The Wavelet Packet Transform (WPT) belongs to the family of the wavelet transform. The basis functions of the WPT are called wavelet packets. Wavelet Packets can recursively be computed using Quadrature Mirror Filter (QMF) pairs *h(n)* and *g(n)*:

$$w_{2n}(t) = \sqrt{2}\sum_{k\in Z} h(k) w_n(2t-k) \qquad (1)$$

$$w_{2n+1}(t) = \sqrt{2}\sum_{k\in Z} g(k) w_n(2t-k) \qquad (2)$$

in which w_n denotes the wavelet packet function, h(n) is the impulse response of a low pass filter and g(n) is the impulse response of a high pass filter. h(n) and g(n) form a QMF pair. They should be satisfied the following condition:

$$g(n) = (-1)^n h(L-n-1) \qquad (3)$$

where L is the span of the filters. The coefficients of filters h and g are calculated by using the following equations:

$$\varphi(t) = \sum_n h(n)\sqrt{2}\varphi(2t-n), \quad n \in Z \qquad (4)$$

$$\psi(t) = \sum_n g(n)\sqrt{2}\varphi(2t-n), \quad n \in Z \qquad (5)$$

In the above equations, $\psi(t)$ and $\varphi(t)$ denote the wavelet function and the scaling function, respectively.

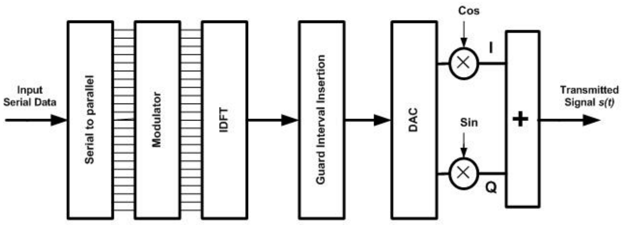

Fig. 1. Block diagram for an OFDM transmitter

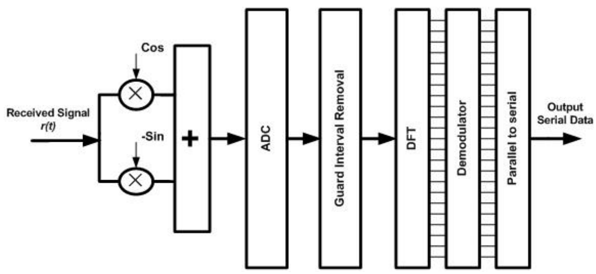

Fig. 2. Block diagram for an OFDM receiver

In WOFDM, the IWPT is employed to conduct data modulation and demodulation process is performed using WPT. Here, the number of subcarriers is determined by the number of stages in the filtering processes i.e., $number\ of\ subcarriers = 2^{number\ of\ stages}$. For example, a 3-stage WPT is depicted in Fig. 3. At every stage, filtering of wavelet coefficients through low and high pass filters, i.e., H and G, results in the wavelet coefficients at a higher stage. The receiver performs the reverse operation of the transmitter.

ACO WOFDM signal is obtained by clipping the WOFDM signal at the zero level and modulating the unipolar signal on the intensity of light. A block diagram of the ACO WOFDM/OFDM system is shown in Fig. 4. To produce the ACO WPT-OFDM signal, the negative parts of the electrical signal should be clipped off. Then, the signal is modulated on the intensity of light. An ACO WPT-OFDM transmitter is shown in Fig. 5.

At the transmitter, a parallel to serial convertor is employed to generate parallel data. Next, each parallel data channel is mapped onto 16-ary Quadrature

Amplitude Modulation (QAM) symbol. The information symbols are then transformed into a complex time domain samples via an IWPT. Guard Interval (GI) insertion is performed. GI acts as a space between successive WOFDM symbols and therefore prevents ISI. A real time passband WOFDM signal is obtained through a DAC and an IQ modulator. The negative parts of the signal are clipped off. The signal is modulated on the intensity of light using an optical modulator, i.e. Mach Zehnder Modulator (MZM). Receiver performs the reverse operations of the transmission scheme to recover the original data.

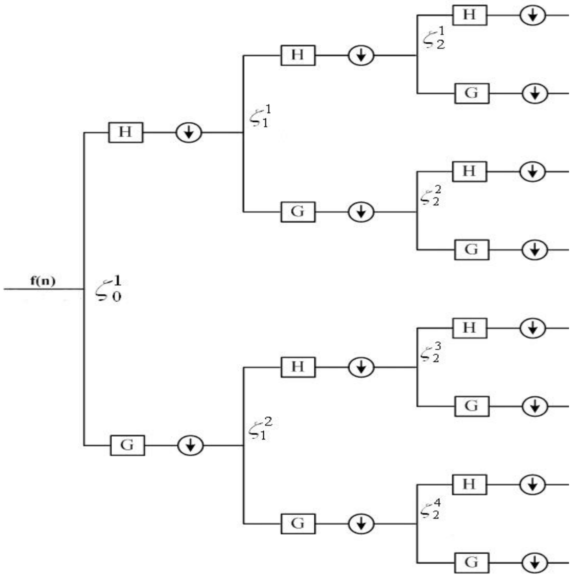

Fig. 3. A 3-Stage WPT

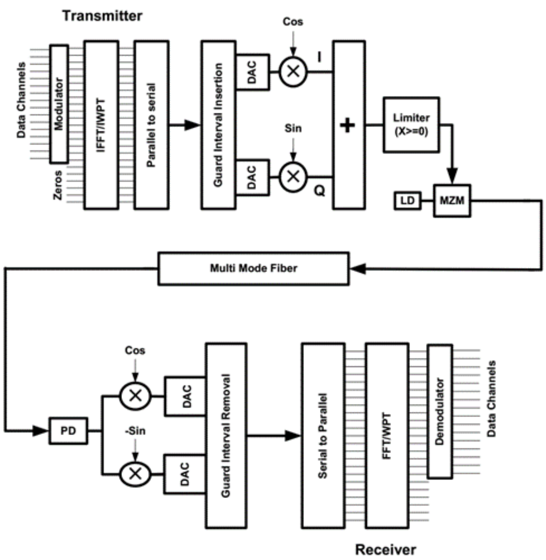

Fig. 4. The simulated ACO WOFDM/OFDM systems

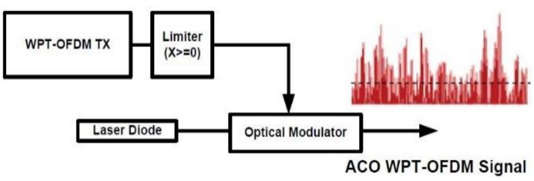

Fig. 5. An ACO WPT-OFDM transmitter.

III. CACO WOFDM

WOFDM transmission is based on the idea that a transmission system can operate at different rates, depending on the channel conditions, or that certain bits will be better protected than others in case of adverse channel conditions. Such behavior of the transmission system can be achieved using different techniques depending on the transmission channel. For example, error protection codes can be used, thus making certain bits more robust than others in the case of a noisy channel. The combination of such a transmission scheme with a coding algorithm is very natural. On the other hand, when considering wavelet packets to adjust the multicarrier system as much as possible to the channel characteristics, one must take care about the frequency content of the wavelets. As mentioned in [4], when performing a low-pass and high-pass filtering on the result of a high-pass filtering, the frequency-contents get switched, so that the high-pass filtered part comes at the lower frequencies, and the low-pass filtered part at the higher frequencies of the original frequency-region. This must be taken into account when ordering the subcarriers in the actual frequency-order to adjust the number of bits on each subcarrier according to the correct subchannel response. If you have a symmetric wavelet tree, it comes down to performing a coding system on the subcarriers to obtain their ordering in frequency.

In this article, we investigate the performance of the Hamming coded ACO WPT-OFDM (CACO-WOFDM) system over a multimode optical channel. In an *(n, k)* linear code, encoder maps each *k-bit* code into an n-bit codeword. Each *n-bit* codeword contains *n-k* parity bits. An *(n, k)* Hamming code is a linear code in which parity bits are located on positions 2^j $(j= 0, 1,\ldots, n\text{-}k\text{-}1)$, while the information bits are located on the remaining positions. For example, for a *(7, 4)* Hamming code, the codeword can be represented by $P_1P_2I_1P_3I_2I_3I_4$, where P_j $(j= 1, 2, 3)$ are parity bits, and I_j $(j= 1, 2, 3, 4)$ are the information bits. The positioning of parity bits in Hamming codes simplifies the decoding process. In other words, the syndrome of the received codeword determines the exact position of the error in the received codeword. Supposing the information bits are $I_1I_2I_3I_4$ = 1101, the corresponding codeword is $P_1P_2 1P_3 101$. The parity check bits are determined as follows:

$P_1 = I_1 + I_2 + I_4 = 1$, $P_2 = I_1 + I_3 + I_4 = 0$, and $P_3 = I_2 + I_3 + I_4 = 0$. As a result, the transmitted codeword becomes $t_1t_2t_3t_4t_5t_6t_7$ = 1010101. Assuming the codeword was received with an error, which is located at the third position, i.e. $r_1r_2r_3r_4r_5r_6r_7$ = 1000101, the syndrome is calculated as: $S_1 = r_1 + r_5 + r_7 = 1$, $S_2 = r_7 = 1$, $S_3 = r_5 + r_7 = 0$, and $S = S_3S_2S_1 = 011$. This implies that the syndrome determines the exact position of the error in the received codeword.

Properties of binary hamming codes are listed as follows: (i) The distance of a Hamming code is three, (ii) for an *(n,k)* binary Hamming code, the following inequality must be valid $2^{(n-k)} \geq n+1$, (iii) They are perfect codes.

The block diagram of the Hamming coded ACO WOFDM (CACO WOFDM) system is depicted in Fig. 6.

The performances of Symlets and Haar wavelets in an ACO WPT-OFDM system has compared [15]. The simulated system is employed for data transmission over a multimode fiber optical link. In this article, the performance of ACO WPT-OFDM is compared to CACO WPT-OFDM in terms of BER and OSNR.

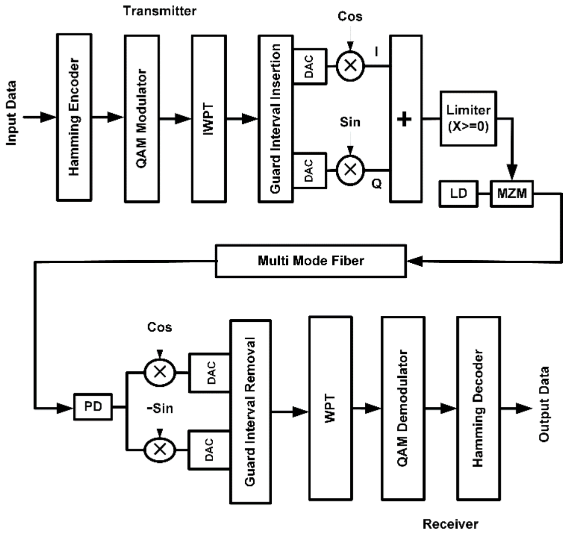

Fig. 6. The CACO WOFDM system.

IV. Simulation and Discussion

Fig. 6 shows the simulation models of the CACO WOFDM and ACO WOFDM systems. Table I lists the simulation parameters. Optisystem software is used to conduct simulations. The optical power of the transmitter laser is 0dBm. The wavelength and linewidth of the laser beam are 850 nm and 10 MHz, respectively. The modal bandwidth of the multimode fiber is 1324 MHz.km; the loss of the fiber is 2.61 dB/km. A PIN photodetector with a dark current of 10 nA and Responsivity of 1 A/W is used to receive the optical signal.

TABLE I. Simulation Parameters

Parameter	ACO OFDM	ACO WOFDM	CACO WOFDM
Carrier frequency	15 GHz	15 GHz	15 GHz
Data rate	10 Gb/s	10 Gb/s	10 Gb/s
Baseband bandwidth	2.5 GHz	1.25 GHz	1.25 GHz
Modulation	16-QAM	16-QAM	16-QAM
Transmitted symbols	28	28	28
Transmitted bits	28784	28784	28784
FFT/WPT points	1024	1024	1024
Subcarriers	1024	1024	1024
Data subcarriers	256	256	256
Pilot subcarriers	64	64	64
Zero subcarriers	768	768	768
Cyclic prefix	128	128	128
Symbol period	115.2 ns	115.2 ns	115.2 ns
Cyclic prefix period	12.8 ns	12.8 ns	12.8 ns
Mother Wavelet	--	Haar, Symlets	Haar, Symlets
Channel Coding	--	--	Hamming Code (7,4)

At the transmitter, the input data bits are first encoded using the Hamming coding algorithm. The Coded data are then mapped onto 16-ary Quadrature Amplitude Modulation (QAM) symbols. The IWPT generates a complex discrete time waveform. The guard interval insertion is performed. The resulting samples are converted into two analog waveforms using P/S conversion followed by a DAC pair. An IQ modulator generates the passband WOFDM signal. The negative parts of the signal are clipped off. The signal is modulated on the intensity of light using an optical modulator, i.e. Mach Zehnder Modulator (MZM). The receiver performs the reverse operation of the transmitter.

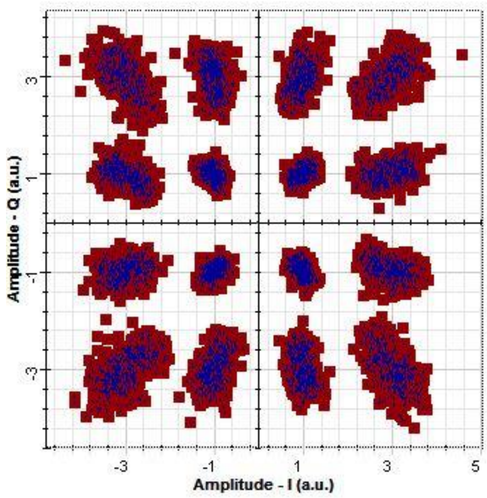

Fig. 7. The received constellations of OFDM symbols after transmitting 135 m.

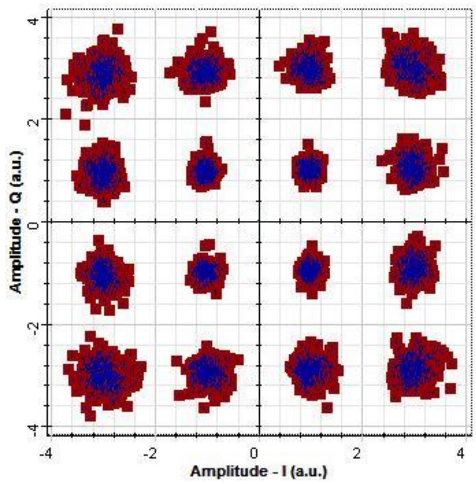

Fig. 8. The received constellations of WOFDM symbols after transmitting 135 m.

The received constellations of ACO OFDM and ACO WOFDM based on Haar wavelet are depicted in Fig. 7

and Fig. 8, respectively. It is evident that the high frequency components of the ACO OFDM signal is more attenuated than the high frequency component of the ACO WOFDM signal. This implies that the spectrum of the ACO WOFDM signal is more compatible with the channel frequency response than the spectrum of the ACO OFDM signal. As well as, Fig. 9 shows the received constellations of CACO WOFDM based on Haar wavelet at 150 m.

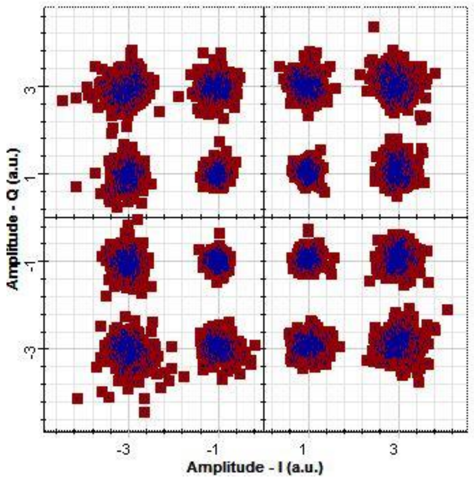

Fig. 9. The received constellations at 150 m.

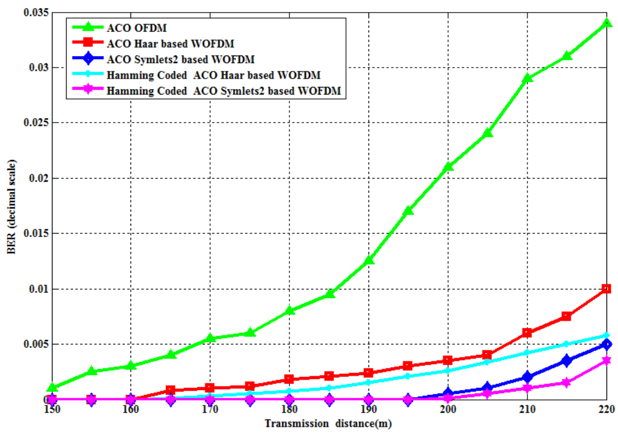

Fig. 10. BER versus transmission distance.

BER and OSNR curves of all mention methods versus transmission distance are depicted in Fig. 10 and Fig. 11, respectively. In Fig. 10, it could be observed that a considerable improvement in BER performance of the ACO WOFDM systems is was observed compared to the ACO OFDM system. It is clear that, the performance of Symlets-based CACO WOFDM better than Haar-based CACO WOFDM. In other words, the Symlets-based scheme works better than the Haar-based WOFDM. There for, the Hamming coded system performs significantly better in terms of the bit error rate values.

Fig. 11 displays OSNR curves for all ACO OFDM systems. The proposed Hamming coded ACO WOFDM system based on Haar wavelet shows better performance than the other systems. The traditional OFDM systems base on FFT has nearly the same OSNR performance. The performance of ACO WOFDM system based on Symlets wavelet has is less than others.

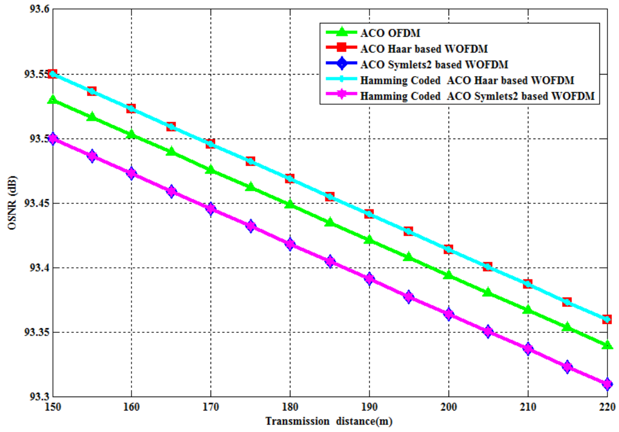

Fig. 11. OSNR versus transmission distance.

V. Conclusions

In this paper, an efficient technique CACO WOFDM system and ACO WOFDM system based on Haar and Symlets wavelets in multimode optical fibers have been proposed. Extensive simulation programs were performed to investigate the efficiency of the proposed system (CACO WOFDM) compared with other OFDM systems based on FFT/WPT.

The BER performance of the Hamming Coded ACO WOFDM system in multimode optical fiber has been investigated. It was found that the ACO WOFDM system based on Symlets wavelet performs significantly better in terms of the bit error rate values. Also ACO WOFDM system based on Haar wavelet performace is better in terms of OSNR. In addition, CACO WOFDM had less BER and high OSNR performance than CAO OFDM systems.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Farhad Sadeghi Almaloo conducted numerical simulation and wrote this paper. Assistant Prof. Majid Zarie gave simulation setting and reviewed this paper. Mahdi Akbari Allah Abadi and Ghader Mohammadi Aghdash gave comments and advises about this proposed method and provided critical feedback and helped shape the research, analysis and manuscript. All authors discussed the approach and results, contributed to the final manuscript and had approved it.

References

[1] Sangeetha and I. S. Rao, "Mitigation of nonlinear effects with volterra and wiener hammerstein electrical equalizer in LDPC coded coherent optical OFDM system," *Journal of Communications*, vol. 14, no. 4, pp. 287-292, 2019.

[2] M. Oltean and M. Nafornita, "Errors per scale statistics for a wavelet OFDM transmission in flat fading channels," in

Proc. IEEE International Symposium on Intelligent Signal Processing, Budapest, 2009, pp. 119-124.
[3] H. C. Yu, Y. R. Chien, and H. W. Tsao, "A study of impulsive noise immunity for wavelet-OFDM-based power line communications," in *Proc. International Conference on Communication Problem-Solving (ICCP)*, Taipei, 2016, pp. 1-2.
[4] W. Hayder Mahdi, Z. H. AL-Azzawi, and N. Taşptnar, "Peak-to-Average power ratio reduction for selective mapping using artificial bee colony algorithm in wavelet packet modulation," in *Proc. 2nd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, Ankara, 2018, pp. 1-6.
[5] M. Chafii, J. Palicot, R. Gribonval, and A. G. Burr, "Power spectral density limitations of the wavelet-OFDM system," in *Proc. 24th European Signal Processing Conference (EUSIPCO)*, Budapest, 2016, pp. 1428-1432.
[6] M. Chafii, Y. J. Harbi, and A. G. Burr, "Wavelet-OFDM vs. OFDM: Performance comparison," in *Proc. 23rd International Conference on Telecommunications (ICT)*, Thessaloniki, 2016, pp. 1-5.
[7] T. Nguyen, M. D. Thieu, and Y. M. Jang, "2D-OFDM for optical camera communication: Principle and implementation," *IEEE Access*, vol. 7, pp. 29405-29424, 2019.
[8] J. Armstrong, "OFDM for optical communications," *Journal of Lightwave Technology*, vol. 27, no. 3, pp. 189-204, Feb. 2009.
[9] X. Zhang, Q. Wang, R. Zhang, S. Chen, and L. Hanzo, "Performance analysis of layered ACO-OFDM," *IEEE Access*, vol. 5, pp. 18366-18381, Aug. 2017.
[10] N. Yin, C. Guo, Y. Yang, P. Luo, and C. Feng, "Asymmetrical and direct current biased optical OFDM for visible light communication with dimming control," in *Proc. IEEE International Conference on Communications Workshops (ICC Workshops)*, Paris, 2017, pp. 23-28.
[11] M. M. A. Mohammed, C. He, and J. Armstrong, "Diversity combining in layered asymmetrically clipped optical OFDM," *Journal of Lightwave Technology*, vol. 35, no. 11, pp. 2078-2085, Jun. 2017.
[12] Z. Hailu, K. Langat, and C. Maina, "Stratified ACO-OFDM modulation for simultaneous transmission of multiple frames both on even and odd subcarriers," *Journal of Communications*, vol. 12, no. 5, pp. 261-270, 2017.
[13] E. Sağ and A. Kavas, "Modelling and performance analysis of 2.5 Gbps Inter-satellite Optical Wireless Communication (IsOWC) system in LEO constellation," *Journal of Communications*, vol. 13, no. 10, pp. 553-558, 2018.
[14] U. K. Kumar and B. S. Umashankar, "Improved hamming code for error detection and correction," in *Proc. 2nd International Symposium on Wireless Pervasive Computing*, San Juan, 2007.
[15] M. E. Tabach, P. Tortelier, R. Pyndiah, and O. Bouchet, "Coded OFDM and OFDM/OQAM for intensity modulated optical wireless systems," *Journal of Communications*, vol. 4, no. 8, pp. 555-564, 2009
[16] A. K. Singh, 'Error detection and correction by hamming code," in *Proc. International Conference on Global Trends in Signal Processing, Information Computing and Communication*, Jalgaon, India, December 2016, pp. 35–37.
[17] W. Rurik and A. Mazumdar, 'Hamming codes as error-reducing codes," in *Proc. IEEE Information Theory Workshop*, Cambridge, England, September 2016, pp. 404–408.
[18] M. Vetterli and J. Kovacevic, *Wavelets and Subband Coding*, New Jersey: Prentice Hall, 2007, pp. 209-325.
[19] F. S. Almaloo, M. Zarie, and G. M. Aghdash, "Investigation of asymmetrically clipped optical wavelet based OFDM system," *Journal of Communications*, vol. 14, no. 9, pp. 833-838, 2019.

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