OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 10, No. 11-12, Nov.-Dec. 2016, p. 873 - 878

Subcarrier exclusion and optimal subcarrier pairing based peak to average power ratio reduction in DD-OOFDM systems

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Orthogonal Frequency Division Multiplexing (OFDM) is a promising modulation technique commonly being used in wired and wireless communications. Recently this technique being implemented in optical fiber communication systems due to its high spectral efficiency, ability to combat both polarization and chromatic dispersions and flexibility in digital signal processing's. However, a major drawback of OFDM is its high Peak to Average Power Ratio (PAPR) which increases with the number of subcarriers. High PAPR requires high dynamic range of Analog to Digital and Digital to Analog converters and power amplifiers. Consequently, PAPR reduction schemes become an essential part of Optical OFDM (OOFDM) systems. In this paper, Optimal Subcarrier Pairing (OSP) technique is proposed to achieve peak power reduction. Further to improve Optical Signal to Noise Ratio (OSNR) for the proposed system to give a certain required value of Bit Error Rate (BER), Subcarrier Exclusion (SE) technique is also proposed. Combination of subcarrier exclusion and optimal subcarrier pairing will provide overall DD-OOFDM system requirements.

(Received November 24, 2015; accepted November 25, 2016)

Keywords: Optimal Subcarrier Pairing (OSP), Peak to Average Power Ratio (PAPR), Subcarrier Exclusion (SE), Optical SNR(OSNR)

1. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique which is now widely being used in most new and emerging broadband wired and wireless communication systems. It belongs to a broader class of Multicarrier Modulation (MCM), in which the data information is carried over many lower rate subcarriers. The advantages of multicarrier modulation technique lie mainly in the fact that in the presence of channel frequency selective fading, only a small part of data is lost. However, in single carrier systems, the whole data stream may get affected. OFDM is robust against channel dispersion and its ease of phase and channel estimation in a time varying environment. It has been dominant in almost every major communication standards, including wireless LAN (IEEE 802.11a/g, digital video and audio standards (DVB/DAB), and Digital subscriber loop (DSL). Worldwide Interoperability for Microwave Access (WiMAX, or IEEE802.16) from the computing community and fourth generation standard Long Term Evolution (LTE) from the telecommunication community, both have adopted OFDM as the core of their physical interface.

OFDM has many advantages such as robustness against frequency selective fading (Narrow band interference), high bandwidth efficiency and efficient implementation. In OFDM modulation, a block of N data symbols X_k (k = 0, 1,…, N-1), of vector **X**, will be transmitted in parallel such that each symbol (X_k) modulates a subcarrier f_k (k = 0, 1,….,N-1). The N subcarriers are considered orthogonal, that is f_k=k.Δf, where f_k = 1/T and T is the OFDM symbol period. The resulting analog baseband OFDM signal x(t) can be expressed as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \, e^{j2\pi f k t} \quad , \quad t \in [0, T] \qquad (1)$$

In practice, the frequency complex symbol vector **X** is transmitted into a discrete time signal **x** = $[x_0, x_1 \ldots x_{N-1}]$ using Inverse Discrete Fourier Transform (IDFT) i.e. **x**= IDFT(**X**). A large number of closely-spaced orthogonal subcarriers are used to carry the data. OFDM consist of a block of 'N' data streams X_k (k=0, 1, …, N-1), of vector X, which will be transmitted in parallel. These 'N' parallel data streams are then used to modulate 'N' orthogonal sub-carriers. Each baseband subcarrier is given as

$$\phi_k(t) = e^{j2\pi f_k t} \qquad (2)$$

where f_k is the k th subcarrier frequency.

The subcarrier frequencies f_k are equally spaced as given by

$$f_k = \frac{k}{NT} \qquad (3)$$

This makes the subcarriers $\phi_k(t)$ on $0 < t < NT$ orthogonal. One OFDM data symbol multiplexes N modulated subcarriers as given as,

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} x_k \phi_k(t), \qquad 0 < t < NT \tag{4}$$

The Optical OFDM has additional advantage of achieving high spectral efficiency in two types, namely Coherent-Optical OFDM (CO-OFDM) and Direct-detection Optical OFDM (DDO-OFDM) [1]. Direct-Detection Optical-OFDM is the method for efficient fiber dispersion compensation for long-haul transmission. In this method, a high-rate signal is encoded into many lower-rate signals, each modulated onto a separate subcarrier [2, 3]. The dispersion is equalized using a single phase shift applied to each subcarrier. It is realized by sending the optical carrier along with the OFDM band so that direct detection with a single photodiode can be used at the receiver to convert the optical field back into the electrical field. A parallel development to DDO-OFDM has been Coherent Optical OFDM (CO-OFDM), which does not transmit the carrier, but instead uses a local oscillator laser at the receiver. CO-OFDM [4-6] requires around 7-dB less Optical Signal to Noise Ratio (OSNR) than DDO-OFDM at the input to the receiver in order to attain the same Bit Error Ratio (BER) at the receiver's output which offers ultimate performance in spectral efficiency, polarization or chromatic dispersion tolerance and receiver sensitivity.

OFDM has two fundamental problems: (i) Frequency offset and Phase noise (ii) Large Peak to average power ratio (PAPR)[7]. Frequency offset and phase noise occurs in OFDM because of its relatively long symbol length compared to that of the single carrier. Frequency offset and phase noise gaining popularity in RF communications. Frequency offset sensitivity can be mitigated through frequency estimation lead to Inter Carrier Interference (ICI). However, these disadvantages obviously have not prevented OFDM from various applications. PAPR is a random variable, because it is a function of input data. Therefore, PAPR can be calculated by finding the average number of times that the envelope of a signal crosses a given level [8]. PAPR is defined as in equation (5):

$$PAPR = \frac{\max_{t \in [0,T]} |x(t)|^2}{E\{|x(t)|^2\}} \tag{5}$$

where E{.} is the expected value operator. In general, most of the signals works in discrete time domain, therefore; we need to oversample the continuous signal x (t) by an over sampling factor of L, which is an integer larger than or equal to one, to approximate true PAPR values. The L-time oversampled signal x_k is given in:

$$x_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n \phi_n(k) \tag{6}$$

where $\phi_n(k) = e^{j2\pi nk/LN}$; for k=0,1,…,LN-1.

PAPR computed from the L-times oversampled time domain signal samples is given in equation (7) as:

$$PAPR = \frac{\max[|x_k|^2]}{E[|x_k|^2]} \tag{7}$$

where $E[|x_k|^2]$ denotes average value over the time duration of OFDM symbol.

From the theory of Central limit theorem, it follows that for a large value of N, both the real and imaginary parts of x_k are Gaussian distributed and therefore the amplitude $|x_k|$ has a Rayleigh distribution. A Cumulative Distribution Function (CDF) of $|x_k|$ is given by

$$F(\zeta) = \mathrm{Prob}\{x_k| \quad \zeta\} \tag{8}$$

$$= \int_0^{\zeta} \frac{2y}{\sigma^2} \exp\left(-\frac{y^2}{\sigma^2}\right) dy \tag{9}$$

$$= 1 - \exp\left(-\frac{\zeta^2}{\sigma^2}\right), \qquad \zeta \geq 0 \tag{10}$$

where $\sigma^2 = E[|X_k|^2]/2$

from the expression(10) we can find that OFDM signals have a high PAPR value.

In this paper, we propose to use Optimal subcarrier pairing with Subcarrier exclusion technique to improve OSNR and overall BER performance of DDO-OFDM systems [9]. In section II we briefly discuss the existing techniques for PAPR reduction in optical based OFDM systems. In section III, the proposed scheme based on OSP with SE is discussed and section IV shows the simulation results supporting the ideas presented. Finally, we summarize our results in section V.

2. Related work

There have been several methods proposed to solve the PAPR reduction in OFDM systems. These methods have different computational complexity and PAPR reduction capability. Partial transmit sequence (PTS) and Selected mapping (SLM) schemes are conventionally used techniques for PAPR reduction [9]. It requires side information to be sent to receiver for proper recovery which results in additional power consumption and data rate loss. Computational and phase search complexity is also exponentially increase in these schemes. Hong and Viterbo (2012) [10] demonstrated that subcarrier pairwise coding is beneficial to direct-detection optical OFDM systems, giving rise in gain where the subcarriers have a 3.2 dB difference in Signal to Interference Noise Ratio (SINR) across the band. It was also observed that when the carrier power is less than the sideband power, which is potentially useful in reducing the effects of fiber nonlinearity. Pairing requires no coding overhead it does not adversely impact on the spectral efficiency of the system. The results are also applicable to any optical OFDM system where subcarriers with poor SINR can be paired with subcarriers of good SINRs. Subcarrier pairing may further improved by employing optimal subcarrier pairing will ensure to achieve required OSNR.

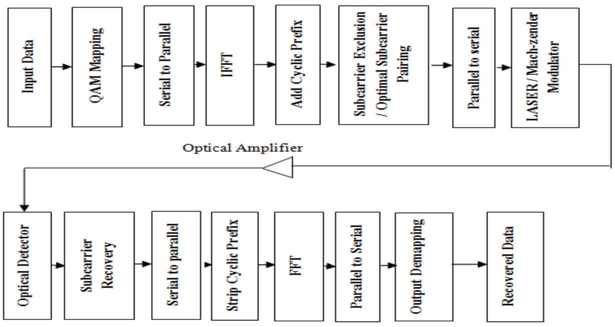

Fig. 1. Proposed DD-Optical OFDM system with SE and OSP

Silva et al. [11] proposed a new peak-to-average power ratio reduction technique based on a Constant Envelope Orthogonal Frequency Division Multiplexing (CE-OFDM) approach to mitigate fiber induced nonlinearities in direct detection optical OFDM [12] systems. Simulation results show that the proposed 10 Gbps DDO-CE-OFDM system using 16-QAM, 2.66 GHz signal bandwidth, and different values of electrical phase modulation index outperforms DDO-OFDM systems as it increases the fiber nonlinearity tolerance in fiber links without optical dispersion compensation. It exploits the advantages of OFDM signals and provides power efficiency, as efficient power amplification can be achieved without causing nonlinear distortion or spectral broadening by a communication system that shares many of the same functional blocks of a standard DFT-based OFDM signaling format. Signal and system definitions of the CE-OFDM format are exploited in this paper. PAPR reduction performance of this scheme is not evaluated for higher number of subcarriers as it raises peak power. So much attention is devoted to reduce the PAPR in OFDM systems.

3. Proposed system

To generate OFDM successfully, the relationship between all the subcarriers must be carefully controlled to maintain the orthogonality of the carriers. For this reason, OFDM is generated by firstly choosing the spectrum required based on the input data and the modulation scheme. Each subcarrier to be produced is assigned some data to transmit. The required amplitude and phase of the subcarrier is calculated based on the modulation scheme such as Quadrature Phase Shift Keying (QPSK) or Quadrature Amplitude Modulation (QAM). In this work we have considered 16-QAM for modulation. The OOFDM transmitter and receiver implementation is as shown in Fig. 1. The input data stream at the rate R_{bps} (R bits/sec) is modulated by a commonly used, more bandwidth and power efficient scheme QAM, resulting in a complex symbol stream X= X[0], X[1],..,X[N − 1]. This symbol stream is passed through a Serial-to-Parallel (S/P) converter, whose output is a set of N-parallel QAM symbols subcarriers. Thus, the N symbols output from the serial-to-parallel converter are the discrete frequency components of the OFDM modulator output s(t). In order to generate s(t), these frequency components are converted into time samples by performing an Inverse Discrete Fourier Transform (IDFT) on these N symbols, which is efficiently implemented using the IFFT algorithm. The IFFT yields the OFDM symbol consisting of the sequence x[n] = x[0], . . . , x[N − 1] of length N. The cyclic prefix is then added to the OFDM symbol to eliminate Inter Symbol Interference (ISI) between data blocks, and the resulting time samples [n]= [-μ],…….…. [N-1]= x[N-μ],……x[0],….x[N-1] are ordered by the Parallel-to-Serial (P/S) converter, where μ is the last values of the sequence x[n].

Subcarrier pairing will work better because each subcarrier has a different electrical Signal to Interference plus Noise Ratio, which typically increases with subcarrier's frequency. The performance of the poor subcarriers degrades the performance of the good subcarrier, therefore we adopt subcarrier exclusion technique to remove very poor subcarrier from pairing. The wanted subcarriers each have a different electrical $SINR_i$, $i = 1,\ldots, N_{sc}$, defined as the ratio of power of OFDM signal at the i-th subcarrier and the noise and interference. To improve the OSNR [8] requirements of DDO-OFDM [11-18], we consider the set of pairs $\beta = \{(p_k,q_k)$, where $k = 1,\ldots,N_{sc}/2\}$ forming a partition and N_{sc} is the total number of subcarriers, where k is the index of pairs. We classify the high subcarriers in bin1 and low subcarrier powers in bin2. According to subcarrier pairing good subcarriers with high SINR in bin1 should be paired with poor subcarriers with low SINR in bin2. Hence; the pairing of the corresponding subcarriers should be optimum combination of good and bad subcarrier pairs. However the optimum subcarrier pairing additionally requires side information to be transmitted to the receiver for recovery of the original subcarriers from optimal pairing done at the transmitter. Received signal is down converted to baseband and filtered to remove the high frequency components. The prefix of y[n] consisting of the first μ samples is then removed. This results in N time samples whose DFT in the absence of noise. These time samples are S/P converted and passed through an FFT. These results in scaled versions of the original symbols associated with the k^{th} sub channel. The FFT output is parallel-to-serial converted and Subcarriers are rearranged at the receiver then passes through a demodulator to recover the original data.

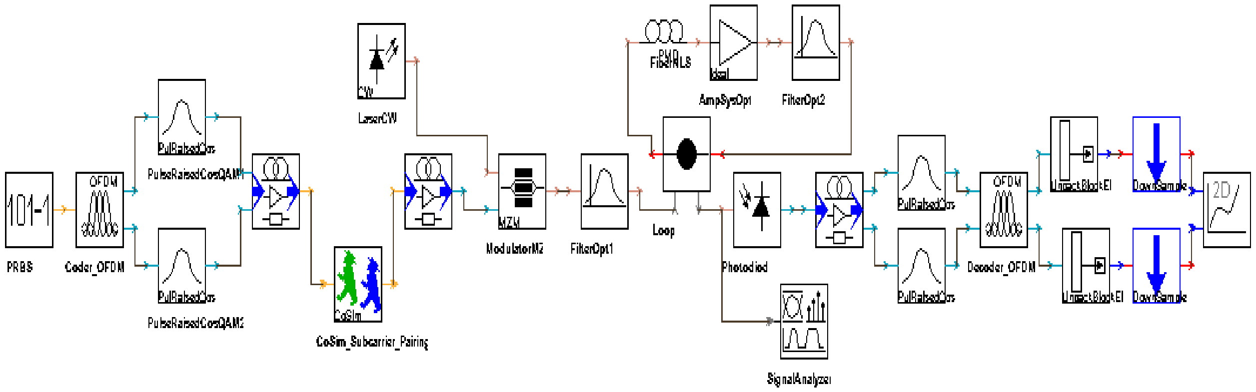

Fig. 2. VPI simulation design

4. Simulation results

The simulation was carried out using Virtual Photonics Integrated (VPI) which is a powerful tool that allows simulating a wide range of optical transmission designs. This allows an easier management of the modules taking part in a simulation, as they can be treated independently or as a group when necessary. The VPI modules can be classified into three levels such as the universe, galaxy and star. A star represents a unique module with a specific function which cannot be subdivided into other modules. A galaxy can be described as a second level module formed by a set of interconnected stars (or even other galaxies). In order to be implemented on a universe, a galaxy must contain at least one input or output port. The universe is the only module that can be executed by the user. It represents the whole simulation scenario, and it can consist of a combination of interconnected stars and galaxies. The parameters of each module can be set or adjusted using the Parameter Editor Window (PEW). Co-simulation is done using MATLAB to find individual subcarrier power for subcarrier exclusion and pairing. Before beginning the simulation the parameters of VPI has to be carefully chosen, the failure of this may cause errors. Since generation of subcarriers includes IFFT algorithm at the transmitter side and its detection includes FFT algorithm at the receiver side, VPI works better when the sample rate and time window parameters are set such that they are in powers of 2. The various parameters associated with the simulation are given in the Table 1.

Table 1. Simulation parameters

Parameter	Specifications
Fiber Length	1000km
Fiber Attenuation	0.2 dB / Km
Bit rate	10 Gbps
Modulation	16-QAM
Number of IFFT / FFT	64
Cyclic Prefix	0.2

Fig. 2 shows the universe schematic of the simulation setup. It consists of three galaxies named as RF up_converter, RF down_converter and MATLAB Co-simulation for subcarrier exclusion and pairing. An important feature of VPI is Cosimulation, which we have exploited in our simulation. The PRBS module provides binary bits at the rate of 10Gbps as input to the ofdm_coder star module. Prior to RF up_conversion, the matlab program is interfaced to find subcarrier powers for subcarrier exclusion and optimal subcarrier pairing. This technique improves implementation of PAPR reduction within the OFDM symbol. The upconverted OFDM signal is then externally modulated using a LASER source. We have applied Machzhender modulator (MZM) to perform optical modulation. This modulated optical signal is now launched into standard single mode fiber of 10 loops with each loop contributing 100Kms of length. Each loop can be assisted with an optical amplifier and an optical filter to produce a better signal constellation. We have chosen single mode fiber because the non-linear effects are low compared to the multimode fiber.

At the receiver side the optical signal is detected using a photodetector. The detected signal is then downconverted using the downconverter module and then fed to the OFDM decoder galaxy which performs the reverse process of the OFDM coder. The demodulated signal can be numerically plotted by using the NumericalAnalyzer1D_vtms module and the optical and electrical signals at various points can be viewed and analysed using Signal Analyzer_vmts module.

Fig. 3 shows the received constellation obtained by plotting the I and Q components of the received signal.

The simulation uses 16-QAM symbol mapping, therefore figure shows 16-points in the constellation.

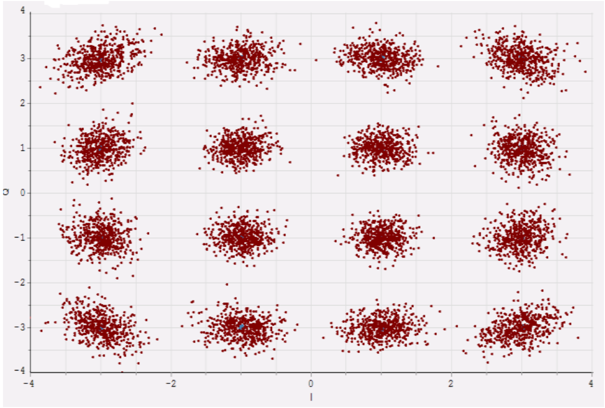

Fig. 3. 16-QAM constellation

Fig. 4 shows the optical power spectrum after the LASER source is externally modulated by using MZM. The frequency values (in GHz) in the x axis are relative to 193.1 THz, so this is the real frequency for the 0 Hz value in the graph. This will also be the frequency for the optical carrier signal, which is separated by a 12.5 GHz gap from both the suppressed lower sideband (left in the graph) and the optical OFDM signal centered at 15 GHz from the optical carrier.

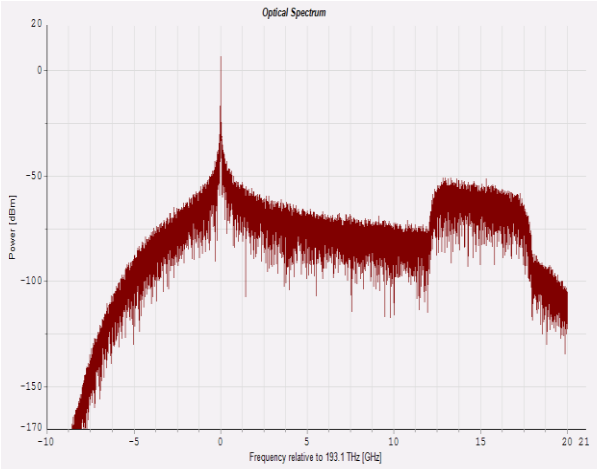

Fig. 4. Received Optical Spectrum

Individual subcarrier power for 16 subcarriers are plotted in Fig. 5. It is observed that few subcarrier powers are very low. In large subcarrier systems few subcarriers carries less power which will affect OSNR at the receiver. Therefore, to improve optical signal to noise ratio performance we proposed to use Subcarrier Exclusion (SE) technique in our system.

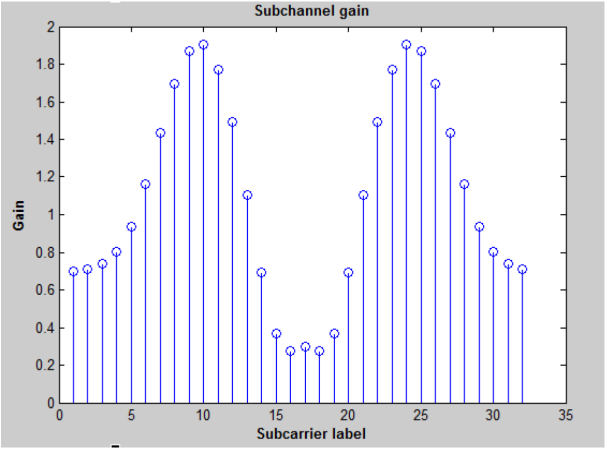

Fig. 5. Individual subcarrier powers

Fig. 6 shows the PAPR reduction performance of proposed technique with Subcarrier exclusion and Subcarrier pairing in DDO-OFDM system. In this Original refers to PAPR reduction without applying any reduction technique. The probability of clipping levels is given as the probability that any part of an OFDM frame is clipped. It may be intuitive to think there is a trivial relationship between the probability of clipping and the BER; however, the relationship is quite complicated. Because BER constraints vary according to application and there are many variables involved in relating a probability-of clipping level to a BER, in this paper we will assume that a probability-of-clipping level of 10^{-4} is reasonable. At the clipping probability of $10^{-4,}$ system without peak power reduction technique offers 11.8dB. After applying SE with OSP, at the same clipping probability the proposed system offers 8.6 dB. Therefore, it is evident that reduction of 3.2 dB is achieved.

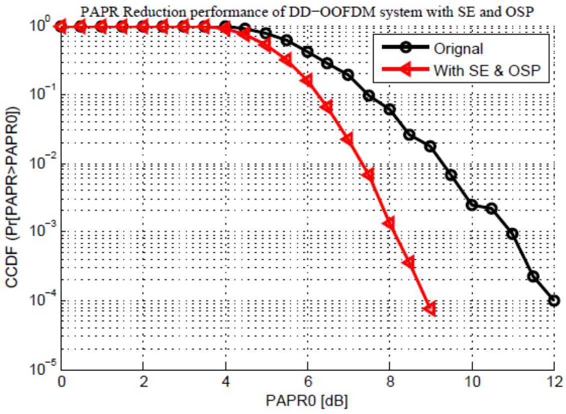

Fig. 6. PAPR Reduction performance of proposed technique with SE and OSP

Symbol error rate of 16- subcarriers are plotted in Fig. 7.

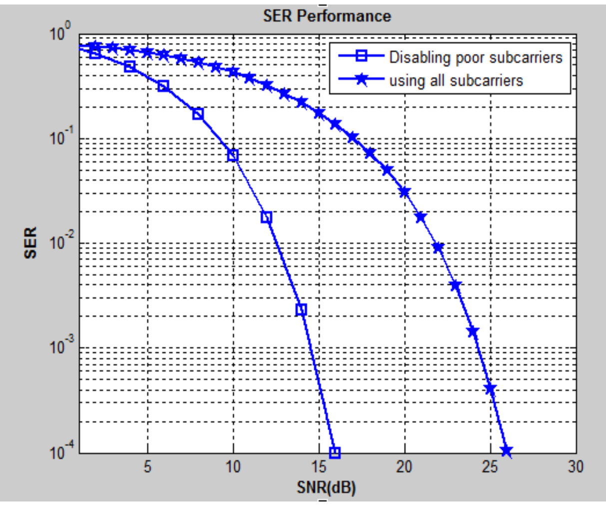

Fig. 7. SER performance of individual subcarriers

Subcarriers are grouped based on their SNR. After necessary SE, optimal subcarrier pairing is done to improve OSNR with required BER.

5. Conclusion

Orthogonal Frequency Division Multiplexing (OFDM) is being implemented in optical fiber communication systems due to its high spectral efficiency, ability to combat both polarization and chromatic dispersions. Direct detection optical OFDM system has proved to be an effective system that mitigates chromatic dispersion. Peak power reduction is achieved by optimal subcarrier pairing technique with subcarrier exclusion technique. Combination of subcarrier exclusion and optimal subcarrier pairing will provide overall OOFDM system requirements.

References

[1] A. J. Lowery, J. Armstrong, in Optical Fiber Communication Conf. 2007.

[2] A. J. Lowery, J. Armstrong, Opt. Express **14**(6), 2079 (2006).

[3] A. J. Lowery, Opt. Express **16**(2), 860 (2008).

[4] W. Shieh, C. Athaudage, Electron. Lett. **42**(10), 587 (2006).

[5] J. V. Hoyningen-Huene, J. Leibrich, A. Ali, W. Rosenkranz, in Optical Fiber Communication Conf. 2011, OWE3.

[6] Q. Yang, W. Shieh, Y. Ma, IEEE Photon. Technol. Lett. **20**(15), 1305 (2008).

[7] S. Han, B. H. Soong, Q. D. La, Tired networks, IEEE Wireless Communications Letters **2**(2), 179 (2013).

[8] S. H. Han, J. H. Lee, IEEE Wireless Commun. **2**, 56 (2005).

[9] Yi Hong, Arthur J. Lowery, Optics Express **20**(2), 1635 (2012).

[10] J. A. Silva, T. M. Alves, A. Cartaxo, M. E. Segatto, in Signal Processing in Photonic Communications 2010, SPThB2.

[11] S. C. Thompson, A. U. Ahmedt, J. G. Proakis, J. R. Zeidler, in IEEE MilitaryCommunications Conf. 1129 (2004).

[12] S. K. Mohammed, E. Viterbo, Y. Hong, A. Chockalingam, IEEE Trans. Inf. Theory **57**(6), 3542 (2011).

[13] W. Shieh, C. Athaudage, Electron. Lett. **42**(10), 587 (2006).

[14] J. Leibrich, A. Ali, H. Paul, W. Rosenkranz, K.-D. Kammeyer, IEEE Photon. Technol. Lett. **15**, 1033 (2009).

[15] B. J. C. Schmidt, A. J. Lowery, J. Armstrong, J. Lightwave Technol. **26**, 196 (2008).

[16] Y. Hong, E. Viterbo, A. J. Lowery, in European Conference on Optical Communications (Geneva, 2011), p. Th.11.B.2.

[17] Serkan Dursun, Artyom M. Grigoryan, Computers and Electrical Engineering, Elsevier, 1055 (2010), DOI:10.1016.

[18] Robert J. Baxley, G. Tong Zhou, IEEE Transactions on Consumer Electronics **50**(3), 792 (2004).

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