OPTIMIZATION OF OPTICAL SSB-OFDM SYSTEM WITH DIRECT DETECTION FOR APPLICATION IN METROPOLITAN/REGIONAL NETWORKS

Bruno M. M. Meireles and João L. Rebola

Department of Information Science and Technology, Instituto Universitário de Lisboa (ISCTE-IUL), Lisboa, Portugal

Group of Research on Optical Fiber Telecommunication Systems, Instituto de Telecomunicações, Lisboa, Portugal

Keywords: Direct-detection, Noise accumulation, Optical add-drop multiplexers, OPTICAL communications, optical fiber, Orthogonal frequency division multiplexing (OFDM).

Abstract: Due to its spectral efficiency, dispersion robustness, simplicity and transparency to electrical modulation format, orthogonal frequency division multiplexing (OFDM) is a promising technique that allows to increase the capacity and to make the upgrade of optical telecommunications systems already installed. In this work, the study and optimization of OFDM transmission in an optical communication system using direct detection with a short and medium range (metropolitan and regional networks) for a target bit rate of 10 Gbps will be performed exhaustively. The optimization is carried out taking into account the impact of noise accumulation and of signal distortion resulting from bandwidth narrowing introduced by the cascade of add-drop multiplexing nodes on the network performance. Optical transmission of single sideband OFDM signals is considered and the carrier-to-signal power ratio of the OFDM signal is optimized in order to achieve the best network performance.

1 INTRODUCTION

Optical frequency division multiplexing (OFDM) is a digital modulation technique that allows transmitting multiple signals simultaneously in a high-speed data channel. The data are separated into narrow parallel subcarriers, where frequency overlapping is possible without intercarrier interference since all subcarriers are orthogonal (Shieh, 2010). Hence, OFDM makes a more efficient use of the spectrum than conventional frequency division multiplexing. Different modulation schemes, such as Quadrature Amplitude Modulation (QAM) or phase shift-keying, can be chosen for the different subcarriers independently (Shieh, 2010). Moreover, since OFDM has a long symbol period allows practically eliminating the intersymbol interference due to fiber channel dispersion (Shieh, 2010).

Another advantage of using OFDM is that electrical channel equalization is done by a single tap equalizer, while single carrier systems require more complex electrical equalization techniques such as adaptive equalization (Schmidt, 2008), (Lowery, 2007).

An important drawback of OFDM is the signal large peak-to-average power ratio (PAPR). OFDM being a superposition of a higher number of modulated subchannels signals may exhibit a high instantaneous signal peak power (Hanzo, 2004). In optical communications, high PAPR can impose higher signal distortion in the presence of fiber nonlinear effects (Shieh, 2008).

Currently there are two types of optical detection used in OFDM transmission: coherent optical OFDM (CO-OFDM) detection and direct-detection OFDM (DD-OFDM). The use of direct detection is widespread in existing optical communication systems. Although, it has lower sensitivity than CO-OFDM systems (Shieh, 2008, 2010), its simplicity and lower cost, makes direct detection suitable for metropolitan/regional networks, which do not require state-of-the-art components as long haul networks do.

Furthermore, the upgrade of installed links to transmit OFDM signals is carried out mainly on the electronic part of the communication link (through

M. M. Meireles B. and L. Rebola J..
OPTIMIZATION OF OPTICAL SSB-OFDM SYSTEM WITH DIRECT DETECTION FOR APPLICATION IN METROPOLITAN/REGIONAL NETWORKS.
DOI: 10.5220/0003488701330138
In *Proceedings of the International Conference on Data Communication Networking and Optical Communication System* (OPTICS-2011), pages 133-138
ISBN: 978-989-8425-69-0

the use of digital signal processing to perform the Fast Fourier Transform (FFT) and its inverse) and not on the existing optical components (Shieh, 2010).

In this work, the performance of an optical DD-OFDM system is studied and optimized, with the objective of using this signalling scheme in metropolitan/regional networks (with about 600 km of total length), where the accumulation of noise and bandwidth narrowing introduced by a cascade of optical nodes can have a significant impact on the network performance.

2 SYSTEM DESCRIPTION

2.1 OFDM Transmitter

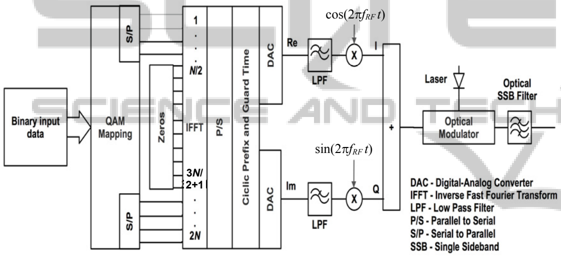


Figure 1: OFDM transmitter architecture.

Figure 1 shows the OFDM transmitter architecture scheme used in this work. The input serial data is first mapped to symbols using QAM. Then, the data symbols are converted into *N* parallel blocks of data (*N* subcarriers). *N* blocks of zeros are inserted in the middle of the data subcarriers, making a total of 2*N* parallel subcarriers within one OFDM symbol. The introduction of these zeros (oversampling), as well as the low pass filter (LPF) before the IQ modulator, is used to reduce the aliasing (Alves, 2009). Then an inverse-FFT is applied to the subcarriers resulting in a time domain waveform that contains a superposition of all 2*N* subcarriers. After, cyclic prefix and guard interval are inserted. The resulting waveform is then modulated by an IQ modulator to a radio frequency (RF) carrier with frequency f_{RF} (Lowery, 2006). Then, the two signal I and Q components are added and the OFDM electrical signal is obtained.

Before optical transmission, the OFDM electrical signal needs to be modulated onto the optical domain using an external modulator (Shieh, 2010). In this work, a Mach-Zehnder modulator (MZM) operating in linear and nonlinear regime will be considered. In the linear regime, no signal distortion is introduced by the MZM. In the nonlinear regime, the bias voltage of the MZM should be chosen to improve the MZM linearity and minimize signal distortion. Hence, the MZM is biased at the quadrature point (Leibrich, 2009). Then, the optical carrier power (in relation to the OFDM signal power) is controlled by the single-side band (SSB) filter, in order to improve the sensitivity of the OFDM reception (Lowery, 2007). After SSB filtering, the OFDM signal is transmitted through a singlemode fiber (SMF).

2.2 OFDM Receiver

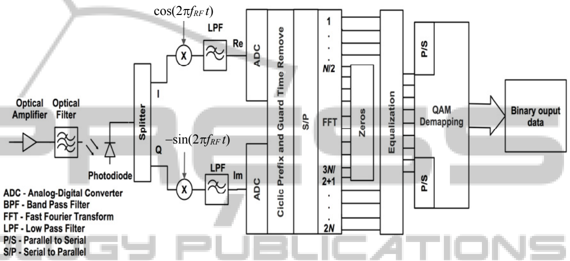


Figure 2: OFDM receiver architecture.

Figure 2 shows the DD-OFDM receiver architecture. The optical receiver includes an optical amplifier, an optical filter followed by a PIN photodetector and by an OFDM electrical receiver. At the OFDM electrical receiver, the baseband signal is recovered using an IQ demodulator with a LPF in each demodulation arm. The resulting baseband signal is sampled using an A/D converter, then cyclic prefix and guard interval are removed and a FFT is applied to the resulting signal.

After FFT, the zero subcarriers are removed and each subcarrier is equalized in order to compensate for phase and amplitude distortion due to transmission (Agrawal, 2004). Equalization is performed by applying the inverse of the estimated channel response using training sequences (Lowery, 2006). After equalization, each sub-channel is demapped and the original bits are recovered. At this point, the DD-OFDM system performance is evaluated by estimating the bit error rate (BER).

2.3 System Performance Evaluation

In order to perform the system performance evaluation, two distinct methods are used: BER estimated using Monte Carlo simulation and direct error count (DEC), which is named BER_{DEC} and is defined per subcarrier *k* by (Alves, 2010).

$$BER_{DEC}[k] = \frac{\text{number of bit errors}}{\text{total number of transmitted bits}} \quad (1)$$

and the BER obtained from the error vector magnitude (EVM), named BER_{EVM} and given by

$$BER_{EVM}[k] = 4 \cdot \frac{1-1/\sqrt{M}}{\log_2 M} \cdot Q\left(\sqrt{\frac{3}{M-1} \cdot \frac{1}{EVM^2_{RMS}[k]}}\right) \quad (2)$$

where M-QAM mapping per subcarrier is assumed and EVM_{RMS} is the root mean square of the EVM defined by

$$EVM_{RMS}[k] = \sqrt{\frac{\sum_{l=1}^{N_s} \left|s_o^{(l)}[k] - s_i^{(l)}[k]\right|^2}{\sum_{l=1}^{N_s} s_i^{(l)}[k]}} \quad (3)$$

In equation (3), N_s is the number of OFDM symbols transmitted per OFDM frame and $s_i^{(l)}[k]$ and $s_o^{(l)}[k]$ are the M-QAM symbols corresponding to the k^{th} subcarrier of the l^{th} OFDM symbol of the ideal constellation and the constellation obtained at the equalizer output, respectively (Alves, 2010).

The BER of the OFDM symbol is obtained by averaging the BERs obtained for all subcarriers.

Although the effect of signal distortion on the system performance is not accurately taken into account using the BER_{EVM} method, when noise accumulation is dominant over signal distortion, the BER_{EVM} provides very precise estimates of the system performance (Alves, 2010).

3 RESULTS

All results have been obtained considering an OFDM signal with the parameters shown in Table 1 for a target bit rate of 10 Gbit/s and are based on the work done by Lowery (2007).

Table 1: Simulation parameters.

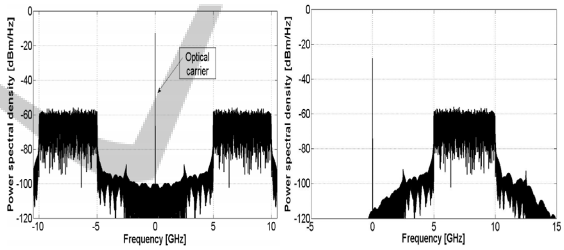
Modulation	Nº of transmitted bits per OFDM symbol	Nº of subcarriers	Bit rate per OFDM stream D_b
4 QAM	1024	512	10 Gbps
OFDM symbol duration - T_S	**Guard interval G_i**	**Cyclic prefix**	**OFDM signal bandwidth**
102.4 ns	7.4206 ns	6.4 ns	≈ 5 GHz

Figure 3 a) shows the power spectral density (lowpass equivalent representation) of the double-sideband (DSB) OFDM signal at the MZM output centered at the RF carrier of 7.5 GHz, with a bandwidth of 5 GHz.

In a preliminary study, the bandwidths of the electrical filters of the OFDM transmitter and receiver have been optimized and 6^{th} order Bessel filters with a bandwidth of 4 GHz and 2.9 GHz, respectively, have been found as optimum and used throughout this work.

3.1 Optical SSB Filter Optimization

In this section, the bandwidth of the optical SSB (OSSB) filter is optimized in order to suppress the optical carrier power and improve the DD-OFDM system performance (Lowery, 2007). Furthermore, the use of SSB signalling (in comparison with DSB), allows to decrease the distortion introduced by the fiber chromatic dispersion during optical transmission. The carrier-to-signal power ratio (CSPR) is defined as $CSPR = P_c/P_{OFDM}$ (Alves, 2010), where P_c is optical carrier power and P_{OFDM} is the SSB OFDM signal power. For illustrative purposes, Figure 3 b) shows the OFDM signal spectrum after the OSSB filter for a CSPR of 0 dB.



a) b)

Figure 3: Power spectral density of the OFDM signal. a) DSB signal at the modulator output. b) SSB signal after filtering for a CSPR of 0 dB.

The optimization is performed by estimating the performance of the DD-OFDM system (using the BER_{DEC} and BER_{EVM}) as a function of the CSPR (by varying the OSSB filter bandwidth) for the optical signal-to-noise ratios (OSNRs) of 11 dB, 15 dB and 20 dB. A 2^{nd} order supergaussian optical filter is considered at the optical receiver. The optimization is performed for an external modulator working in the linear (Figure 4) and nonlinear (Figure 5) regimes.

Figure 4 shows that for an OSNR of 11 and 15 dB, the optimum CSPR is 0 dB as predicted in the works by Lowery (2006, 2007) and Jansen (2007). This corresponds to an OSSB filter bandwidth of 5 GHz. For an OSNR of 20 dB, it is possible to observe that the optimum value is shifted to higher CSPR values and therefore higher OSSB filter bandwidths. This shift of the CSPR for higher OSNRs has been also observed in the work by

Jansen (2007) and is attributed to the higher influence of the intermixing of OFDM subcarriers after the photodetection [the photodetection mixing products are described in detail by Lowery (2008)] on the performance, when the amplified spontaneous emission (ASE) noise power is lower.

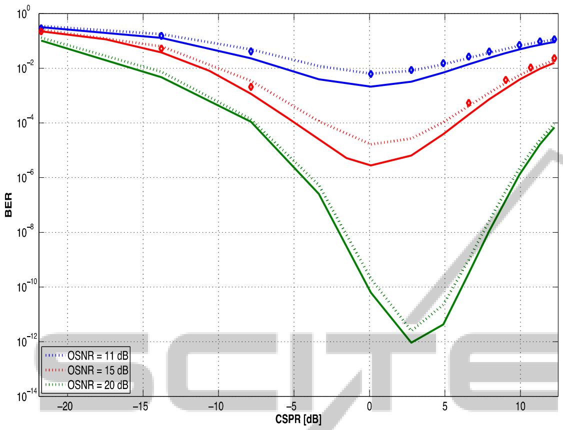


Figure 4: BER_{EVM} and BER_{DEC} (diamonds) as a function of the CSPR for the OSNRs of 11 dB (blue), 15 dB (red) and 20 dB (green), for a linear external modulator and for the receiver optical filter bandwidths of 100 GHz (dashed lines) and 30 GHz (continuous lines).

Figure 4 shows also a good agreement between the error probabilities estimated using the BER_{DEC} and the BER_{EVM} for lower OSNRs, in accordance with the results presented in the work by Alves (2010). Furthermore, it shows that the performance of the DD-OFDM system is improved by using the receiver optical filter with a bandwidth of 30 GHz, due to higher ASE noise power reduction.

Figure 5 shows the BER as a function of the CSPR, for the nonlinear external modulator, for different modulation indexes *m*. It is possible to observe that the optimum CSPR value is always near 0 dB, although, for higher modulation indexes, a slight shift of the optimum CSPR is observable. It is also possible to observe that, as the bandwidth of the SSB filter increases (higher CSPR) and for higher modulation indexes, the distortion due to the external modulation non-linear regime starts to impose the system performance. For lower modulation indexes, the external modulator is operating near the linear regime and the noise is the main performance impairment, once the distortion induced by the external modulator on the OFDM signal is negligible.

Moreover, it is possible to infer that for a DSB-OFDM signal (which corresponds to the rightmost CSPR depicted for each modulation index), there exists an optimum value for the modulation index, which leads to the best system performance. This conclusion is in agreement with the results presented in the work by Alves (2010).

Figure 5 shows again a good agreement between the estimates of the BER obtained using the BER_{DEC} and the BER_{EVM}.

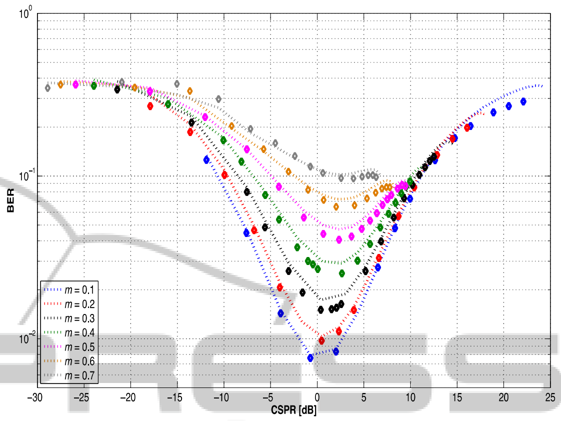


Figure 5: BER_{EVM} (dashed lines) and BER_{DEC} (diamonds) as a function of the CSPR for the model of the nonlinear external modulator for different modulation indexes (*m*) and an OSNR of 11 dB.

3.2 OFDM Signal Transmission along a Cascade of Optical Nodes

In this section, the transmission of OFDM signals along an optical communication system with several fiber spans is studied. The impact of noise accumulation and of bandwidth narrowing along the several spans on the performance of the DD-OFDM system will be investigated. Figure 6 shows the scheme considered for the OFDM transmission system, with a special emphasis on the optical node configuration. The optical fiber considered in this investigation is a standard singlemode fiber with a dispersion parameter D_λ = 17 ps/(nm.km) and an attenuation of α =0.2 dB/km. Linear transmission along the fiber is considered.

The optical node is simply modelled by an ideal inline optical amplifier with gain *G*, which adds ASE noise to the signal (operation performed in the simulation by a noise generator) and an optical filter to reduce the noise power. In this scheme, the noise added by each erbium-doped fiber amplifier (EDFA) accumulates along the link. Notice also that the signal distortion can be enhanced at the photodetector's input due to the cascade of optical filters. It is also assumed that the optical amplifier exactly compensates the fiber attenuation. In a first approach, we also considered that fiber dispersion is completely compensated by the electrical equalizer.

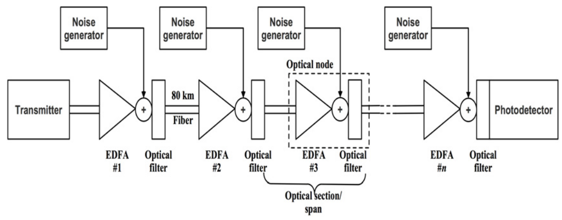


Figure 6: OFDM transmission system with several spans. Each span is composed by a fiber followed by the optical node constitute by an EDFA and an optical filter.

It is worth recalling that one of the main goals of this work is to study OFDM transmission in a metropolitan/regional optical network, which has about 600 km of distance coverage. So, it is important to estimate the DD-OFDM system performance for the optical link depicted in Figure 6, and to determine if the commitment for the network coverage length is accomplished.

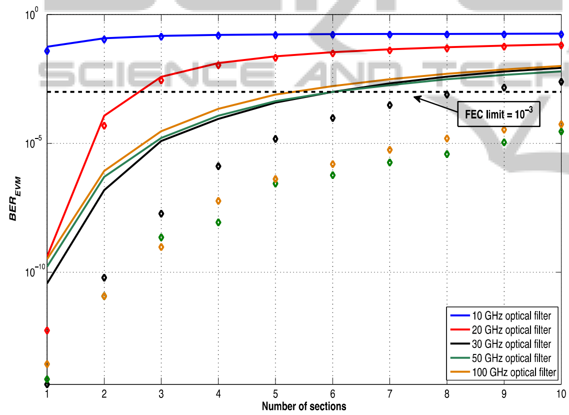


Figure 7: BER_{EVM} as a function of the number of sections used in the optical link obtained for an OSNR of 25 dB (diamonds) and 20 dB (continuous lines) for different receiver optical filter bandwidths. The error probability corresponding to the FEC limit is also depicted.

Figure 7 shows the error probability estimated using the BER_{EVM} as a function of the number of sections for different receiver optical filters. The MZM is assumed to be working in the linear regime at the optimum CSPR. Figure 7 shows that the probability of error increases as the number of optical sections increases, since the OSNR is degrading with the number of sections. For the optical filters with a bandwidth of 10 GHz (blue) and 20 GHz (red), the distortion suffered by the OFDM signal (due the smaller optical filter bandwidth and severe bandwidth narrowing due to the cascade of optical nodes) is dominant over the noise and no distinction is found between the error probabilities estimated for both OSNRs of 20 dB and 25 dB (measured at the output of the first optical node). For higher optical bandwidths (larger than 30 GHz), the signal distortion introduced by the optical filtering is not so significant and noise accumulation along the optical link plays an increasing role on degrading the network performance. Similar conclusions were found for the nonlinear MZM model, as long as it is working in lower modulation indexes (near the linear regime).

Only BER_{EVM} results are presented, since when noise is the dominant factor that impairs the system performance (over signal distortion), BER_{EVM} provides very accurate BER results (Alves, 2010).

To achieve the objective of covering a metropolitan/regional network with a length of about 600 km and by assuming that each fiber section is about 80 km long, approximately 8 sections are needed to cover that distance [by considering that the error probability is bounded to the value of 10^{-3}, which corresponds to the limit for forward error correction (FEC) (Shieh, 2010)]. From Figure 7, one can conclude that, for an OSNR of 25 dB, the goal of covering the typical maximum distance of metropolitan/regional network is accomplished.

Then, the impact of optical fiber transmission on the system performance is evaluated to confirm if the distortion imposed by the optical fiber dispersion is indeed compensated by the equalizer and can be considered negligible or not. The results obtained are shown in Figure 8.

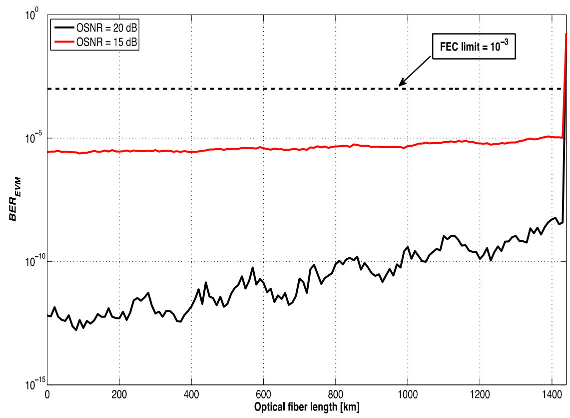


Figure 8: BER_{EVM} as a function of the optical fiber length in the optical link. The error probability corresponding to the FEC limit is also depicted.

Figure 8 shows that for an OSNR of 20 dB and for a fiber length up to 600 km, the OFDM system error probability is always below 10^{-10}. Therefore, it is possible to state that the distortion imposed by the SMF is sufficiently compensated by the equalizer. The small oscillations observed in the BER are attributed to the imperfect estimation of the equalizer coefficients for each fiber length. A more accurate coefficients estimation would lead to a less oscillatory BER variation with the fiber length. For an OSNR of 15 dB, as the noise power is higher, the influence of the imperfect estimation of the equalizer coefficients is not visible, and the BER variation with the fiber length shows practically no oscillations for fiber lengths below 1400 km. After 1400 km, the effect of fiber dispersion on the signal can no longer be compensated by the equalizer, due to the insufficient guard interval duration of the OFDM signal (Shieh, 2010) and a peak of the error probability occurs [as shown in Figure 8]. This means that, it is possible to reach a fiber length of approximately 1400 km without significant distortion added by the SMF on the OFDM transmission system. In conjunction with the results presented in Figure 7, it can be stated that the distortion introduced by the optical fiber along the target distance of about 600 km is negligible, and that noise accumulation and signal distortion due to bandwidth narrowing along a chain of optical multiplexing nodes are the dominant factors causing the performance degradation for typical distances of metropolitan/regional networks.

4 CONCLUSIONS

In this paper, it has been shown that it is possible to cover a metropolitan/regional optical network using an optical OFDM system with direct detection at the bit rate of 10 Gbit/s. The optical OFDM system has been optimized in order to attain the best network performance and it has been shown that the error probability is still below the FEC limit after 8 sections of optical nodes (for a typical distance of about 600 km). This conclusion was obtained for an OSNR of 25 dB and for optical filters (inside the optical node) with a bandwidth above 30 GHz. ASE noise accumulation and signal distortion resulting from bandwidth narrowing play a significant role on achieving this limit. We have also found that the distortion introduced by the optical fiber along the network link length is negligible.

The consideration of a more realistic model for the optical multiplexing node based on, for example, reconfigurable optical add-drop multiplexers and the study of the impact of the detuning of the optical filters (inside the optical nodes) on the network performance are left for future work.

REFERENCES

Agrawal G., 2004, *Lightwave Technology – Components and Devices*, John Wiley & Sons, New Jersey, 1st edition.

Alves, T., Cartaxo, A., 2009, "Performance degradation due to OFDM-UWB radio signal transmission along dispersive single-mode fiber", *IEEE Photonics Technology Letters*, vol. 21, no. 3, pp. 158-160, Feb.

Alves, T., Cartaxo, A., 2010, "Analysis of methods of performance evaluation of direct-detection orthogonal frequency division multiplexing communication systems", *Fiber and Integrated Optics*, vol. 29, no. 3, pp. 170-186, May.

Hanzo, L., Münster, M., Choi, B., Keller, T., 2004, *OFDM and MC-CDMA for broadband multi-user communications, WLANs and broadcasting*, IEEE Press, Chichester, 1st edition.

Jansen, S., Morita, I., Tanaka, H., 2007, Carrier-to-signal power ratio in fiber-optic SSB-OFDM transmission systems, *International Conference on Electrical and Computer Engineering IEICE*, Mongaguá, Santos, Brazil.

Leibrich, J., Ali, A., Paul, H., Rosenkranz, W., Kammeyer, K., 2009, "Impact of modulator bias on the OSNR requirement of direct-detection optical OFDM", *IEEE Photonics Technology Letters*, vol. 21, no. 15, pp. 1033-1035, Aug.

Lowery, A., Armstrong, J., 2006, "Orthogonal-frequency-division multiplexing for dispersion compensation of long-haul optical systems", *Optics Express*, vol. 14, no. 6, pp. 2079-2084, Mar.

Lowery, A., Du, L., Armstrong, J., 2007, "Performance of optical OFDM in ultralong-haul WDM lightwave systems", *Journal of Lightwave Technology*, vol. 25, no. 1, pp. 131-138, Jan.

Lowery, A., 2008, "Amplified-spontaneous noise limit of optical OFDM lightwave systems", *Optics Express*, vol. 16, no. 2, pp. 860-865, Jan.

Schmidt, B., Lowery, A., Armstrong, J., 2008, "Experimental demonstrations of electronic dispersion compensation for long-haul transmission using direct-detection optical OFDM", *Journal of Lightwave Technology*, vol. 26, no. 1, pp. 196-203, Jan.

Shieh, W., Bao, H., Tang, Y., 2008, "Coherent optical OFDM: theory and design", *Optics Express*, vol. 16, no. 2, pp. 841-859, Jan.

Shieh, W., Djordjevic, I., 2010, *Orthogonal Frequency Division Multiplexing for Optical Communications*, Academic Press, San Diego, 1st edition.