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Design Issues of Optical Orthogonal Frequency Division Multiplexing System

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Abstract

Optical OFDM (OOFDM) has recently been proposed and the proof-of-concept transmission experiments have shown its extreme robustness against chromatic dispersion and polarization mode dispersion. In this paper, we first review the theoretical fundamentals for OOFDM and its channel model in back to back OFDM representation. We then evaluate the value of RIN for its optimum performance.

Keywords: Fast Fourier Transform (FFT), Polarization mode dispersion (PMD), Self-phase modulation (SPM).

Introduction

Optical orthogonal frequency-division multiplexing (OFDM) has been recently proposed in response to the above-mentioned challenges [1]. OFDM is a multicarrier transmission technique where a data stream is carried with many lower-rate subcarrier tones [2]. It has emerged as the leading physical-layer interface in wireless communications in the last decade. OFDM has been widely studied in mobile communications to combat hostile frequency-selective fading and has been incorporated into wireless network standards (802.11a/g WiFi, HiperLAN2, 802.16 WiMAX) and digital audio and video broadcasting (DAB and DVB-T) in Europe, Asia, Australia, and other parts of the world. OFDM combines the advantages of 'coherent detection' and 'OFDM modulation' and posses many merits that are critical for future high-speed fiber transmission systems. First, the chromatic dispersion and polarization mode dispersion (PMD) of the transmission system can be effectively estimated and mitigated. Second, the spectra of OFDM subcarriers are partially overlapped, resulting in high optical spectral efficiency. Third, by using direct up/down conversion, the electrical bandwidth requirement can be greatly reduced for the OFDM transceiver, which is extremely attractive for the high-speed circuit design, where electrical signal bandwidth dictates the cost. At last, the signal processing in the OFDM transceiver can take advantage of the efficient algorithm of Fast Fourier Transform (FFT)/Inverse Fast Fourier Transform (IFFT), which suggests that OFDM has superior scalability over the channel dispersion and data rate. OFDM was first proposed to combat chromatic dispersion. It was soon extended to polarization-diversity detection, and has been shown to be resilient to fiber PMD [3]. The first OFDM transmission experiment has been reported for 1000 km SSMF transmission at 8 Gb/s [4], and more OFDM transmission experiment has quickly been reported for 4160 km SSMF transmission at 20 Gb/s [5]. The first COOFDM transmission with polarization-diversity has recently been demonstrated showing record PMD tolerance [6]. In the same report [6], the first experiment of nonlinearity mitigation has also been reported for OFDM systems. Although this paper places a focus on the coherent flavour of optical OFDM, we would like to stress that the direct detection flavour of optical OFDM has also been actively pursued by other groups, with applications including multimode fiber transmission [7-8], short-haul single-mode transmission [9], and long haul transmission [10-11].

In this paper, we focus our attention on the theory and design aspects of OFDM. We first review the theoretical fundamentals for OFDM. We then present various design choices for OFDM systems as well as the nonlinearity analysis for the OFDM RF-tooptical up-converter. We also show the receiver-based digital signal processing to mitigate self-phase modulation (SPM) and Gordon-Mollenauer phase noise.

Theory

The output of semiconductor laser exhibit fluctuations in its intensity, phase and frequency even when the laser is biased at constant current with negligible current fluctuations. The two fundamental noise mechanisms are spontaneous emission and electron hole recombination. Noise in semiconductor lasers is dominated by spontaneous emission. Each spontaneously emitted photon adds a small field component to the coherent field (established by stimulation emission), which is random in nature and thus perturbs the both amplitude and phase in a random manner. The occurrence rate of such a spontaneously emitted random field is about 10^{12} s^{-1} [1-3]. Because of which intensity and phase of emitted light exhibit fluctuations over a time scale as short as 100ps. Intensity fluctuations lead to the limited signal to noise ratio (SNR) where as phase fluctuations leads to the finite spectral linewidth when semiconductor lasers are operated at constant current. Clearly such fluctuations lead to the degradation of system performance, therefore it is important to estimate their magnitude. Amplitude fluctuations are characterized by a factor called as Relative Intensity to Noise ratio (RIN)

System Description

The simulation set-up for modeling of RIN determination method using standard fibers is shown in Figure 1.

Figure 1 shows the an OFDM system back-to-back. Graphically the topology is divided in two horizontal levels, the upper one corresponding to the transmitter section and the lower one corresponding to the receiver section with eventually three separate terminations to compare the effects of different options in the model FFTOFDM. A single 10 Gbit/s preudo-random bit sequence is converted into a number of lower rate bit sequences controlled by the symbol *QAM_bit_number*. In fact the multiplicity of the serial-to-parallel conversion corresponds to the number of bits used by the model MQAMIQ to encode one QAM symbol. An intermediate binary to Gray-code conversion is used in the modulation process.

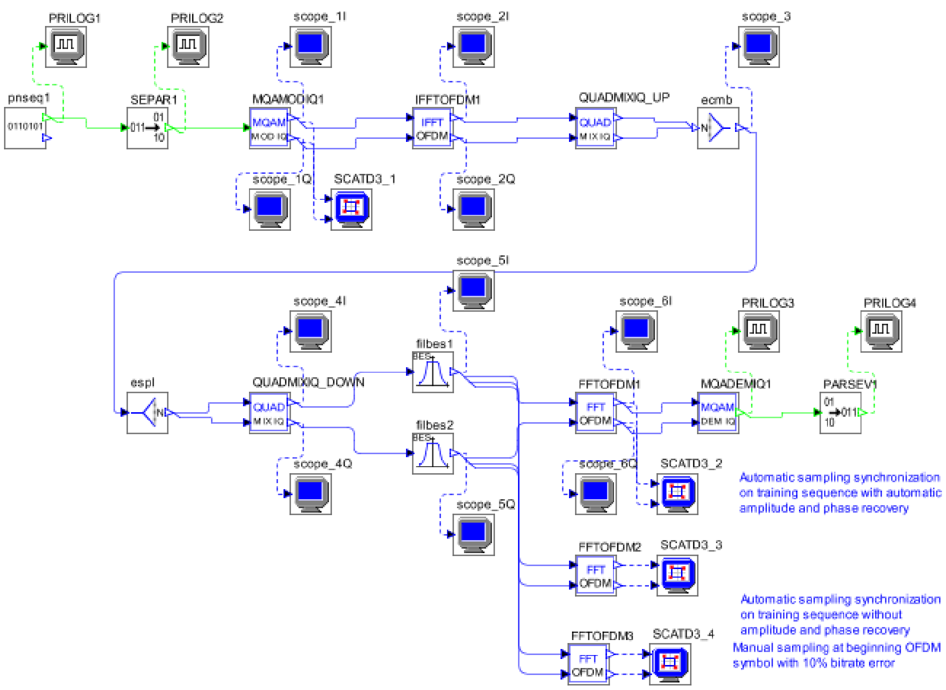

Figure 1: System set-up.

Figure 2 shows the constellation diagram at the output of the QAM modulator obtained with the component *SCATD3*_1. Next the model IFFTOFDM converts the QAM symbols in OFDM symbols with an IFFT operation using a number of subcarriers controlled by the symbol *subcarriers_number*,both accepting in input and returning on output baseband in-phase and in-quadrature signals.

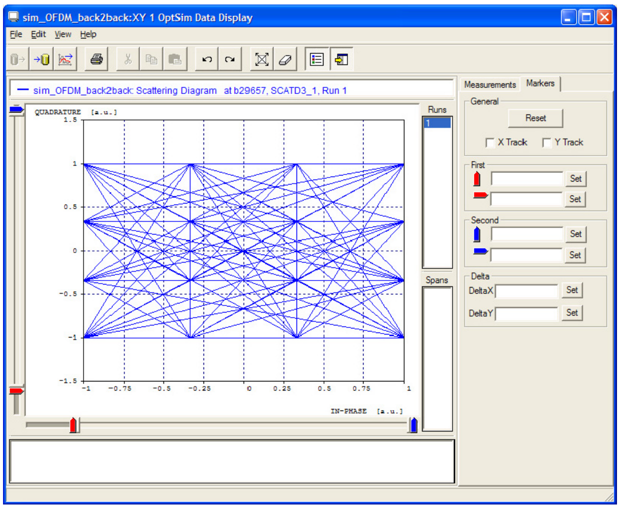

Figure 2: 16-QAM constellation diagram at SCATD3_1.

Figure 3 shows the in-phase component of the OFDM signal at *scope_2I*. Finally the OFDM signal at baseband is RF modulated with a quadrature mixing upconversion at *QUADMIXIQ_UP*.

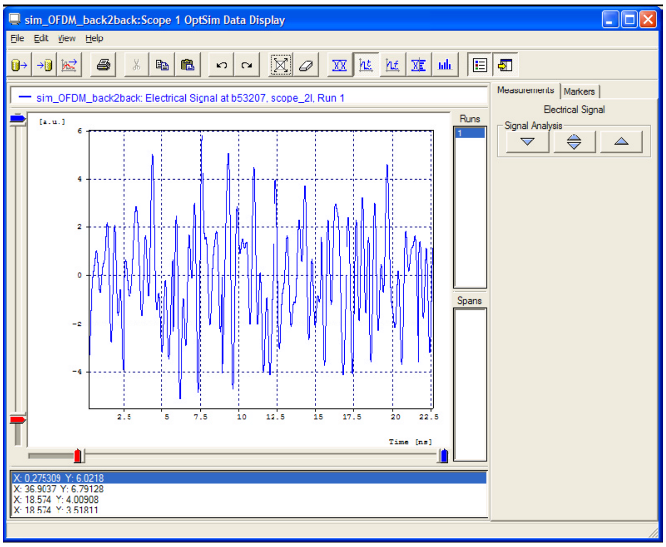

Figure 3: In-phase component of OFDM signal at scope_2.

Figure 4 shows the OFDM signal RF-modulated at *scope_3*. At the receiver section the RF signal is translated to baseband with a quadrature mixing downconversion at *QUADMIXIQ_DOWN*. The replica at twice the carrier frequency originated by the down conversion process is filtered out using two 7-pole low-pass Bessel filters centered at the carrier frequency, 10 GHz.

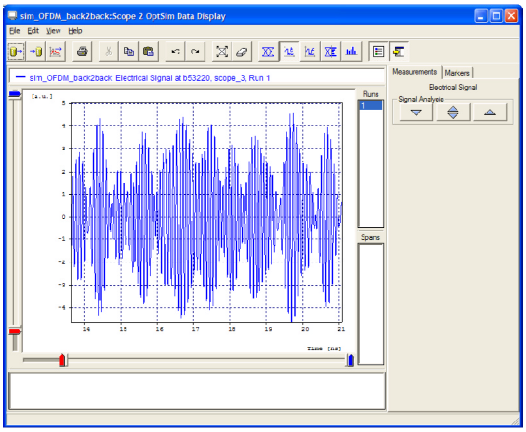

Figure 4: OFDM signal RF-modulated at scope_3.

Figure 5 shows the in-phase component of the OFDM signal at *scope_5I* connected to the output of the low-pass filter. Finally the model FFTOFDM extracts the transmitted QAM symbols from the OFDM signal at baseband with an FFT operation. The OFDM modulation is very sensitive to the sampling instant at the receiver. Not sampling the OFDM symbol at the optimum sampling instant results in very fast deterioration of the system performance. For this reason the OptSim models IFFTOFDM and FFTOFDM include the option to use a training sequence to automatically find the optimum sampling instant. Moreover the model FFTOFDM can also automatically recover the amplitude and phase of the original QAM symbols, thus facilitating the demodulation into bit streams of the received QAM signal.

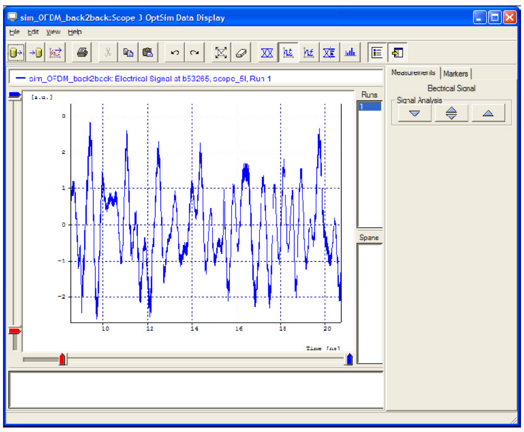

Figure 5: In-phase component of OFDM signal after RF modulation and demodulation at scope_5I.

Figure 6 the received QAM constellation with various combinations of the FFTOFDM options controlling automatic synchronization and amplitude/gain recovery. Finally the received QAM symbols are converted into low-rate parallel bit streams at *MQADEMIQ1* and into a single high-rate bit sequence with a parallel-to-serial conversion at *PARSEV1*.

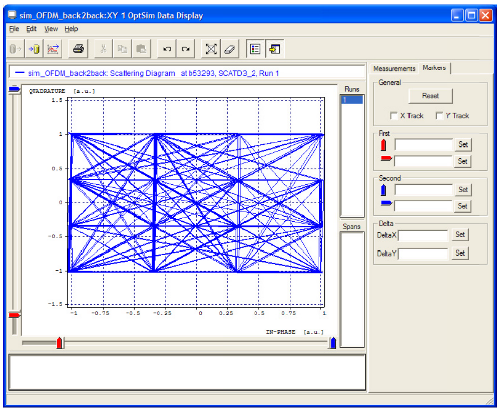

Figure 6: 16- QAM received constellation with automatic synchronization and amplitude/gain recovery at SCATD3_2.

Results and Discussions

A pseudo random sequence length of bits taken one bit per symbol is used to obtain realistic output values at the receiver. Firstly, to observe the impact of RIN upon system performance, simulation results are obtained for linewidth. It is investigated that it causes a sudden fall in optical power with gradual increase in the linewidth for the pulse. Iterations were carried out in the simulation setup in which linewidth varied from 1.23 to 14 (refer Table 1). It was observed that increase in linewidth causes degradation of system performance as BER, timing jitter and Q values degraded drastically. Output electric power correlated with linewidth and results are shown in Figure 7. The output electrical power remains almost constant up to linewidth value of 6-7MHz but as the linewidth value is increased further and approaches14 MHz, there is a loss of optical power measuring 50% and even more.

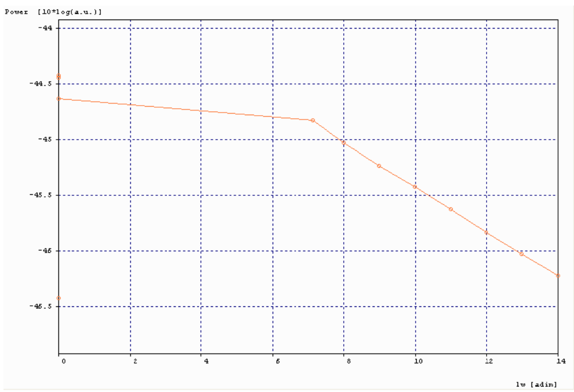

Figure 7: Response of output power w.r.t linewidth.

Eye opening is defined as the difference between the minimum values of the samples decided as logical one and maximum value of the sample decided as logical zero. Average eye opening corresponds to difference between the average values for the samples. It is observed that as the linewidth and receiver attenuation is increased, the eye opening decreases. This can be explained on the basis of the fact that increase in linewidth or the receiver attenuation will introduce more dominance to RIN and its cumulative effect with fiber nonlinearities. The ratio of average eye opening to the eye opening expressed in dB is a measure of eye closure penalty. The plot of this penalty and relative intensity to noise parameter (r) is shown in Figure 8. Further, RIN is correlated with Q value as shown in Figure 9 and it is investigated that its value should be negative.

Table 1: Iterations for Attenuation, Linewidth and RIN.

S.No	No. of Runs	Rx Attenuation	Line width	RIN
	Run 1	0	1.23	10
	Run 2	0.1	4.24	00
	Run 3	0.2	7.13	-10
	Run 4	0.3	8	-50
	Run 5	0.4	9	-80
	Run 6	0.5	10	-90
	Run 7	0.6	11	-120
	Run 8	0.7	12	-150
	Run 9	0.8	13	-170
	Run 10	0.9	14	-180

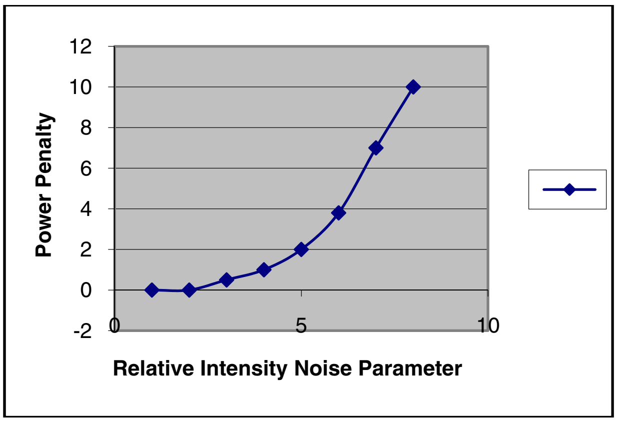

Figure 8: Response of power Penalty w.r.t RIN parameter.

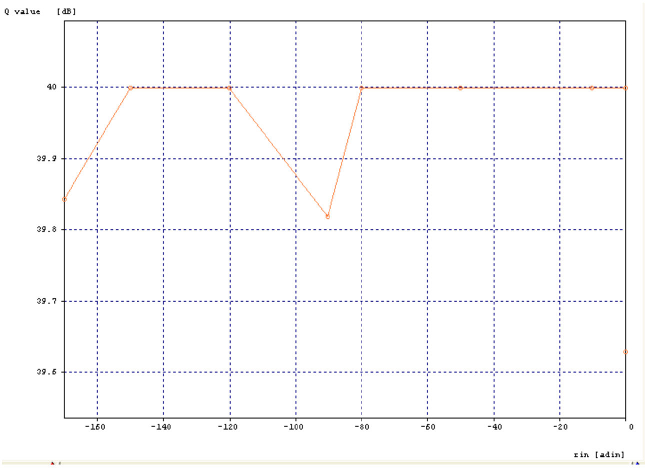

Figure 9: Response of Q value w.r.t RIN.

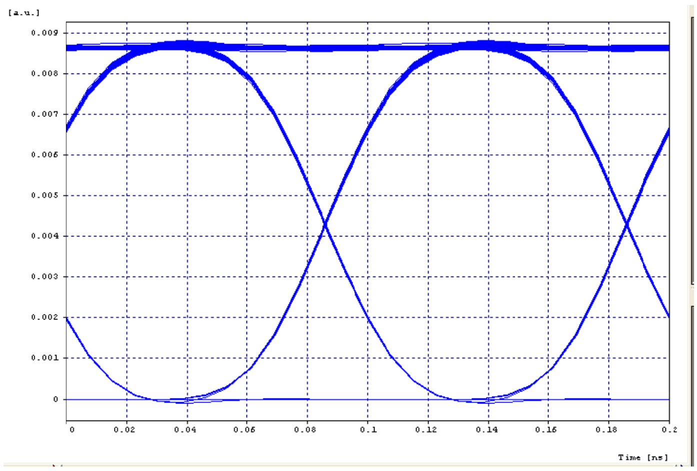

Figure 10: Eye pattern for RIN = -155 dB/Hz and Linewidth = 6.5 MHz.

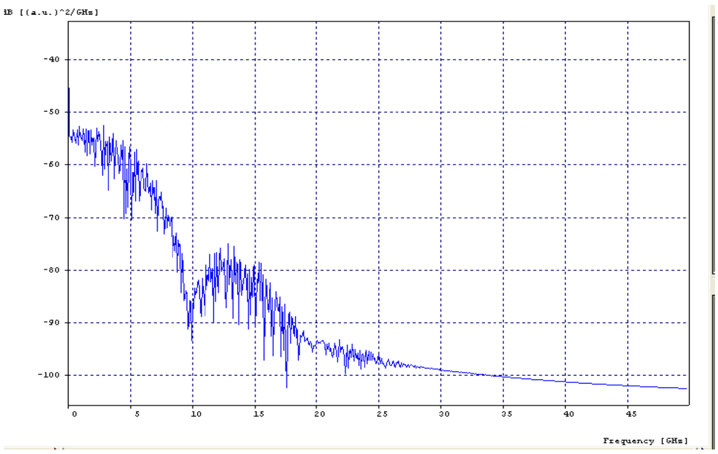

Figure 11: Output spectrum for RIN = -155 dB/Hz and Linewidth = 6.5 MHz.

For positive values of RIN, Q value is found to be very less as compared with the negative values of RIN. In this paper we have iterated the values of RIN from 10 dB/Hz to -180 dB/Hz and different parameters are observed. We found that Q value remains constant for negative values of RIN up to around -120 dB/Hz with further decrease in its value Q value decreases and again tends to be constant up to -160.dB/Hz.

Conclusion

In this paper, we have first reviewed the theoretical fundamentals for OOFDM. We then present various design choices for OOFDM systems as well as the nonlinearity analysis for OFDM RF-to-optical up-converter. We also show the receiver-based digital signal processing to mitigate self-phase modulation (SPM) and Gordon-Mollenauer phase noise. We have concluded that linewidth of pulse has a remarkable effect upon system performance. It is investigated that increase in linewidth results in increase in RIN and hence performance of system degrades. RIN values for a link length of 150 km were obtained while taking into account the fiber non-linearities and polarization mode dispersion effect. We investigated the optimal values for linewidth and RIN for better performance. The limiting value of linewidth should be 6.5MHz up to which optical power remains almost constant and RIN value corresponding to this linewidth is measured to be -155 dB/Hz. and the average value of RIN is measured to be -125 dB/Hz..

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