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Sampling Synchronization for Optimum Performance 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 present various design choices for Automatic sampling synchronization on training sequences without amplitude and phase recovery.

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

Introduction

There are two trends which are ever evident in today's optical networks: (i) the transmission data rate per channel has been fast increasing and rapidly approaching 100 Gb/s, and (ii) the dynamically reconfigurable network has gradually become a reality thanks to deployment of optical Add/Drop Multiplexers (OADM). These trends place significant challenges to the high-speed transmission link for the optical networks. In particular, as the transmission rate approaches 100 Gb/s, conventional meticulous per-span optical dispersion compensation becomes too costly and time-consuming if not possible, as the dispersion compensation requires precise fiber dispersion measurement and precise matching of the dispersion compensation cross broad wavelength range. Most importantly, a dynamically reconfigurable network mandates a fast link setup and leaves the manual optical dispersion compensation impractical. 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 [1]. 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 OOFDM 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-to optical up-converter.

Theory

Principle of orthogonal frequency-division multiplexing (OFDM)

OFDM is a special form of a broader class of multi-carrier modulation (MCM), a generic implementation of which is depicted in Fig. 1. The structure of a complex mixer (IQ modulator/demodulator), which is commonly used in MCM systems, is also shown in the figure.

The MCM transmitted signal *s*(*t*) is represented as

$$S(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{SC}} C_{ki} S_k \left(t - iT_s\right)$$

where *cki* is the *i*th information symbol at the *k*th subcarrier, *k s* is the waveform for the *k*th subcarrier, *Nsc* is the number of subcarriers, *fk* is the frequency of the subcarrier, and *Ts* is the symbol period. The optimum detector for each subcarrier could use a filter that matches the subcarrier waveform, or a correlator matched to the subcarrier as shown in Fig. 1.

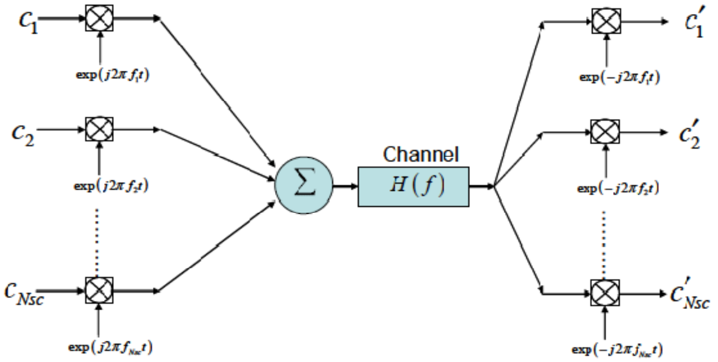


Figure 1: Conceptual diagram for a generic multi-carrier modulation (MCM) system.

The corresponding architecture using DFT/IDFT and digital-to-analog/analog-to-digital converter (DAC/ADC) are shown in Fig. 2.

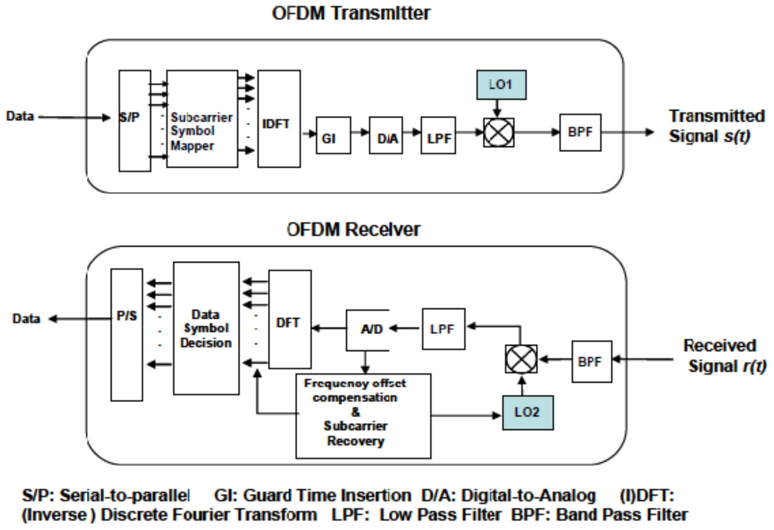
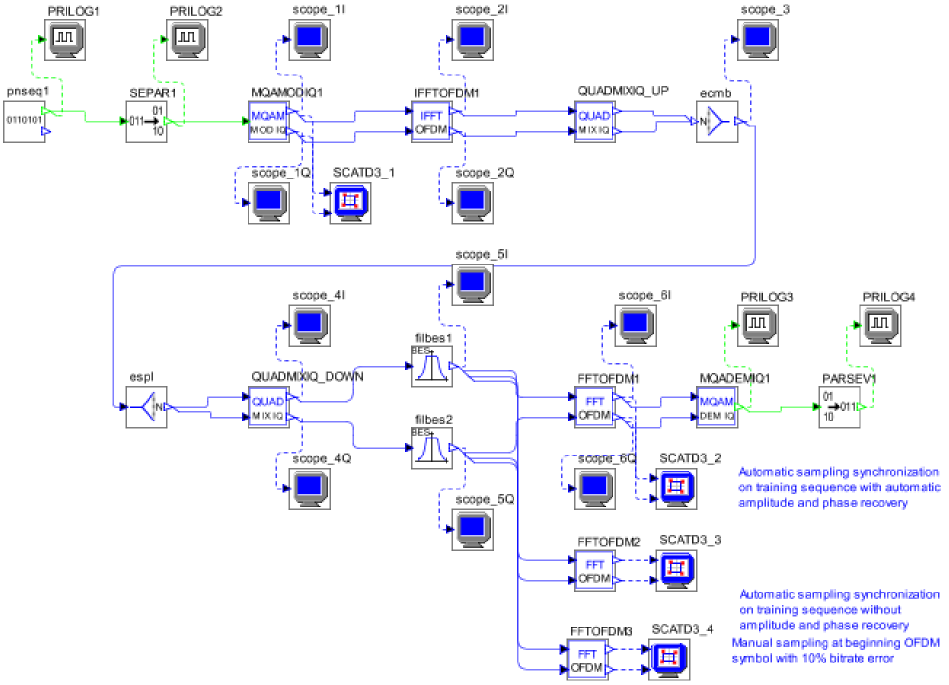


Figure 2: Conceptual diagram for the OFDM transmitter and receiver.

System Description

The simulation set-up for modeling of OOFDM system using standard fibers is shown in Fig. 3.

Fig. 3. 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 pseudo-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.



Automatic sampling synchronization on training sequence with automatic amplitude and phase recovery

Automatic sampling synchronization on training sequence without amplitude and phase recovery

Manual sampling at beginning OFDM symbol with 10% bitrate error

Figure 3: Simulation set-up.

Fig. 4 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.

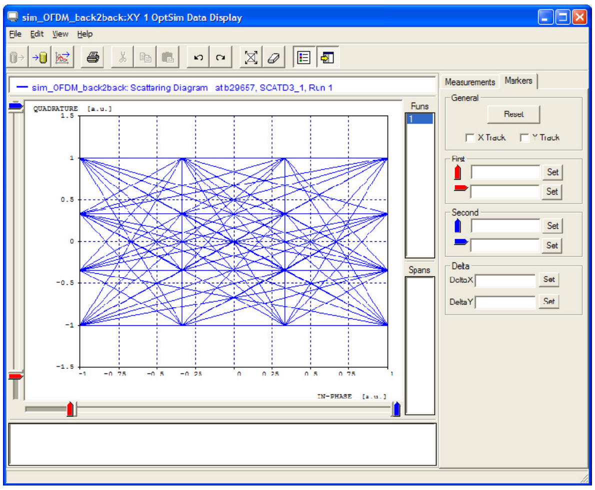
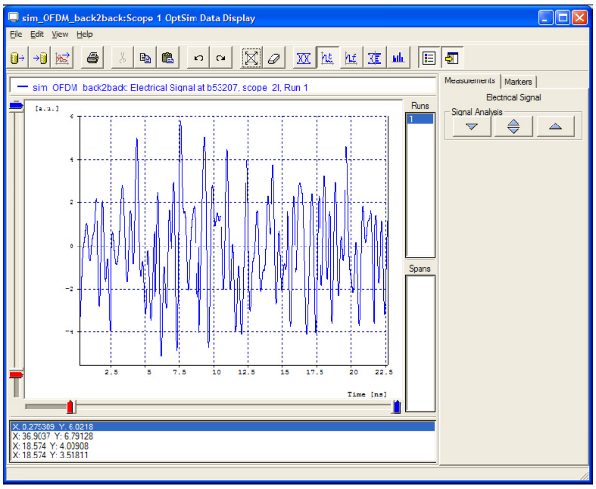


Figure 4: 16-QAM constellation diagram at SCATD3_1.

Fig.5. 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.



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X. 0.275309  Y. 6.0218
X: 36.9037  Y: 6.79128
X: 18.574  Y: 4.00908
X: 18.574  Y: 3.51811
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Figure 5: In-phase component of OFDM signal at scope_2I.

Fig.6. shows the OFDM signal RF-modulated at scope_3. At the receiver section the RF signal is translated to baseband with a quadrature mixing down conversion 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 .

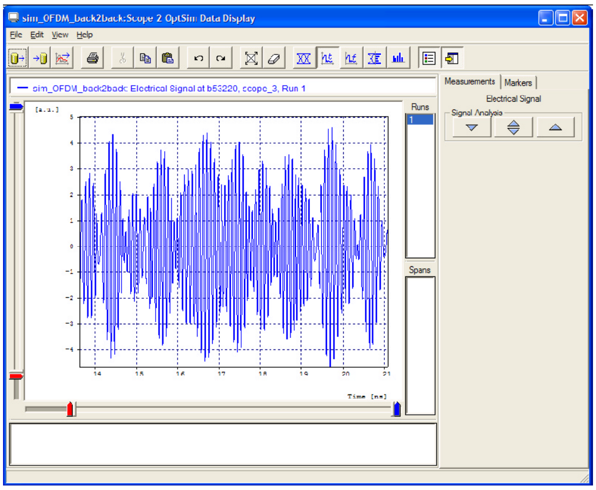

Figure 6: OFDM signal RF-modulated at scope_3.

Fig.7. 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.

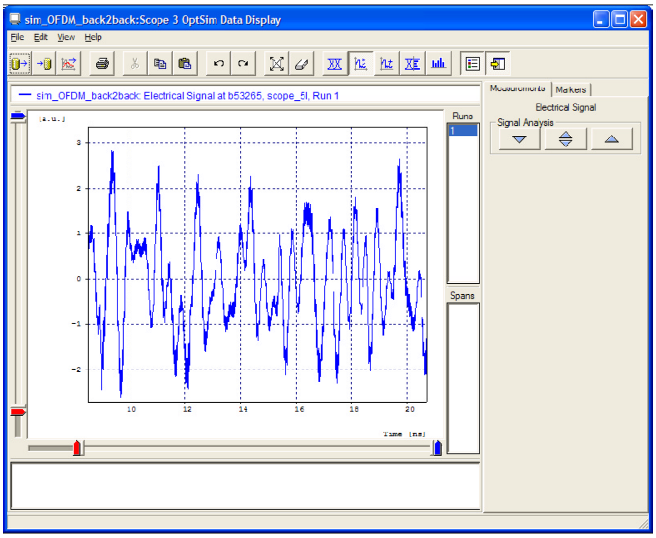

Figure 7: In-phase component of OFDM signal after RF modulation and demodulation at scope_5I.

Fig.8.shows 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.

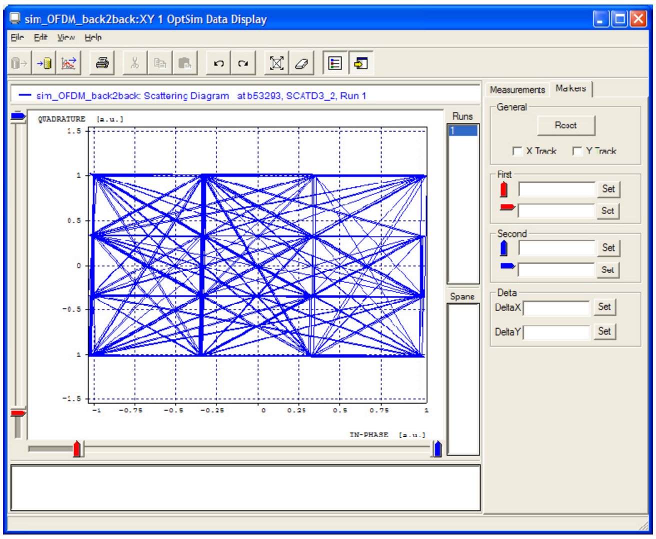

Figure 8: 16- QAM received constellation with automatic synchronization and amplitude/gain recovery at SCATD3_2.

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.

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