

Optical OFDM - A Candidate for Future Long-Haul Optical Transmission Systems

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Abstract: We review coherent-optical orthogonal frequency division multiplexing (OFDM) for long-haul optical transmission systems. Two important aspects of such systems are reviewed: RF-aided phase noise compensation and polarization division multiplexing enabled by MIMO processing.

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1. Introduction

Long-haul optical transmission links are evolving more and more towards dynamically reconfigurable networks. In such networks the flexibility can greatly be increased by using modulation techniques that do not require a complex link design or optimized dispersion map. Orthogonal frequency division multiplexing (OFDM) has recently received a lot of attention as an effective technique to eliminate virtually all inter-symbol interference (ISI) caused by chromatic dispersion [1] and polarization mode dispersion (PMD) [2]. Furthermore, the confined and narrow spectrum of OFDM makes it an ideal candidate for networks with many reconfigurable optical add and drop multiplexers (ROADMs).

For fiber-optic transmission systems, OFDM comes in two flavors, namely direct-detected optical OFDM (DDO-OFDM) [3]-[5] and coherent-optical OFDM (CO-OFDM) [1], [2]. DDO-OFDM 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 domain. In a CO-OFDM system, the optical carrier is suppressed at the transmitter and the receiver is realized by coherent detection with a local oscillator. The superior performance of CO-OFDM with respect to optical signal-to-noise ratio (OSNR) requirements, PMD tolerance and spectral efficiency makes it an excellent candidate for long-haul transmission systems, whereas DDO-OFDM is more suitable for cost-effective short reach applications. The main disadvantages of CO-OFDM are that coherent detection is polarization dependent and that CO-OFDM is very sensitive to phase noise of the local oscillator [6].

In this paper, the performance of CO-OFDM for long-haul transmission systems is discussed. In particular, phase noise compensation and polarization diverse detection are addressed. A novel compensation technique is discussed to overcome phase noise impairments: RF-aided phase noise compensation. Furthermore, polarization division multiplexing (PDM) enabled by multiple-input multiple-output (MIMO) processing is described to overcome the polarization dependence of the coherent receiver and double the spectral efficiency at the same time.

2. Phase noise compensation

The influence of phase noise in OFDM systems is twofold, i.e., it generates a common phase rotation (CPR) of all the subcarriers in one symbol and a cross-leakage between the subcarriers named inter-carrier interference (ICI). The former effect is commonly solved in wireless systems using common phase estimation (CPE) [7], aided by inserting dedicated pilot subcarriers. At the receiver these are used to rotate back the received symbols. This method has been used as well in several fiber-optic transmission experiments, see e.g. [2]. The main drawback of CPE, however, is that it does not correct for the ICI, since it inherently assumes the phase of the transmitter (TX) and local oscillator (LO) laser to be constant during one OFDM symbol. Consequently, the OFDM symbol must be short and the phase noise bandwidth of the TX and LO laser must be small to limit the impact of the ICI. Short OFDM symbols allow for smaller FFT size and thus increase the overhead ratio due to the cyclic prefix. In order to minimize laser phase noise, (complicated) lasers with narrow linewidth must be used. In practice, CPE limits the FFT size to 128 and the linewidth to about 100 kHz [2]. It has been shown that the performance of CPE can be increased [8], however, at the cost of significant receiver complexity.

Recently we introduced a novel phase noise compensation method called RF-aided phase noise compensation (PNC) [9], which effectively compensates for both the CPR and the ICI. With this technique PNC is realized by placing an RF-pilot tone in the middle of the OFDM spectrum at the transmitter, which is subsequently used at the receiver to revert phase noise impairments. The basic idea behind this PNC scheme is as follows. When an RF-pilot

is inserted at the transmitter, this pilot is distorted by phase noise in exactly the same way as the OFDM signal. Therefore the pilot can be used at the receiver to revert any phase distortions from the OFDM signal. Several implementations of RF-aided PNC have been proposed [9]-[11]. Fig. 1a shows the receiver configuration as discussed in [11]. In a heterodyne receiver, an intermediate frequency (IF) is present after coherent detection (as illustrated in Fig. 1b). This IF is first removed by an electrical IQ mixer basically shifting the center frequency of the OFDM band (where the RF-pilot tone is located) to a frequency near DC. Subsequently, the OFDM signal is split and in one of the branches the RF-pilot is selected with a low pass filter (LPF). After the LPF, the RF-pilot is conjugated and multiplied with the OFDM signal. With this implementation, not only the phase noise, but also the residual frequency offset between the TX and the LO laser is compensated for. Therefore, the downmixing frequency of the IQ-mixer does not need to be exactly equal to the IF, but must only make sure that after downmixing, the RF-pilot falls within the range of the LPF. The electrical IQ downmixer is implemented digitally and can therefore be used as well be adjusted to account for laser drifts. In general, laser drifts are significantly slower than the OFDM symbol rate and, hence, a low-speed tracking algorithm can be used.

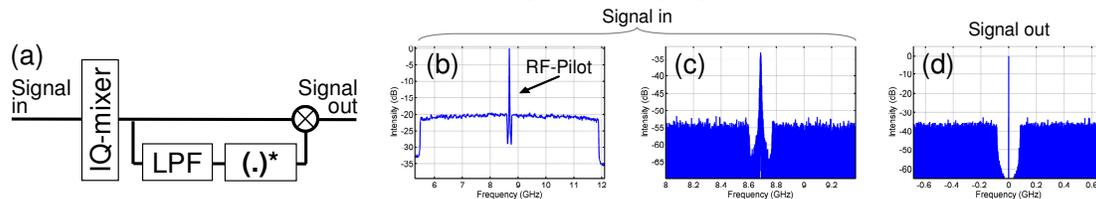


Fig. 1: (a) concept of RF-aided phase noise compensation, (b) Electrical spectrum (10 MHz res. bw.) of the OFDM signal at the receiver before RF-aided PNC (“Signal in”), (c) Zoom in on the RF-pilot of Fig. 1b with 1.25 kHz res. bw., (d) Electrical spectrum (1.25 kHz res. bw.) of the OFDM signal after RF-aided PNC (“Signal out”).

Recently, we have shown that using RF-aided PNC, conventional distribute feedback (DFB) lasers can be used at both TX and LO and that the FFT size can be increased to 1024 [12]. Compared to an external cavity laser (ECL) with a typical linewidth of 100 kHz, an OSNR penalty of 1 dB was observed for the configuration with two DFB lasers at a BER of 1×10^{-3} . The typical linewidth of the DFB laser used in this experiment is 5 MHz, and in order to completely compensate for the phase noise in this experiment, a BPF with 140-MHz bandwidth is required. The subcarrier spacing in this experiment is approximately 10 MHz and therefore 16 extra subcarriers around the DC-subcarrier where zero padded so that the subcarriers did not interfere with the RF-pilot at the receiver. The electrical spectrum of the RF-pilot, the zero-padded subcarriers around the RF-pilot and the surrounding OFDM subcarriers is shown in Fig. 1c and 1d.

3. PDM enabled by MIMO processing

PDM is a very effective method to double the spectral efficiency of a transmission system. However, PDM has a reduced tolerance to PMD, because the polarization de-multiplexing introduces crosstalk between the polarization tributaries [13]. In [14] it has been shown that in combination with coherent detection, PDM can effectively be described as a polarization multiple-input multiple-output (MIMO) system in which any space time coding algorithm can be applied. This has enabled the demonstration of various single-carrier MIMO experiments [15], [16]. Recently we reported PDM for OFDM (multi-carrier) transmission systems with coherent detection [1]. The concept of such a transmission system is shown in Fig. 2.

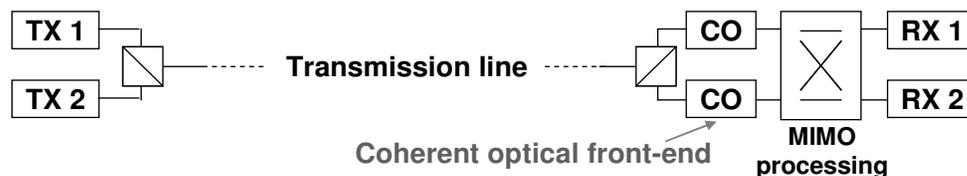


Fig. 2: Concept of PDM enabled by MIMO processing at the receiver.

At the transmitter two signals are multiplexed onto orthogonal polarizations by a polarization beam splitter. The receiver is realized by splitting up the signal into two random polarizations. Subsequently, two coherent optical front-ends are used to convert the signal from the optical to the electrical domain. The two detected signals contain parts of TX 1 and TX 2. MIMO processing is then applied to de-rotate the polarization and separate the two received signals. A straight-forward implementation is zero-forcing MIMO processing, which is realized by multiplying the signal after the FFT with the inverse of the estimated channel matrix to find an estimate of the transmitted vector [7].

The MIMO concept applies for DDO-OFDM as well, however, in this configuration an additional polarization control is required at the receiver to equally split the power of the optical carrier over the two optical front-ends in order to realize a polarization diverse receiver [17].

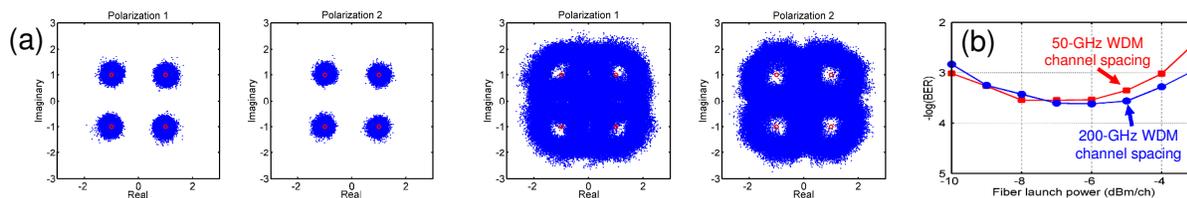


Fig. 3a: Received constellation diagram of the 52.5-Gb/s signal with (left) and without (right) MIMO processing, b) Power excursion after 2,560 km transmission.

A detailed description of the PDM-CO-OFDM transmission experiment is given in [1]. In this experiment transmission of 16x52.5-Gb/s PDM-CO-OFDM channels at 50-GHz WDM spacing was realized over 4,160-km SSMF with large amounts of PMD. The constellation diagrams with and without MIMO processing are shown in Fig. 3a. It can be seen that through MIMO processing a clear constellation diagram is obtained. In back-to-back configuration an OSNR of 11.3 dB (0.1 nm res. bw.) is required to obtain a BER of 1×10^{-3} . This is comparable to the sensitivity of coherent detected PDM-RZ-DQPSK at the same net data rate [16]. Fig. 3b shows the BER as a function of the fiber launch power after 10 recirculations (3,200-km transmission). In this figure, the BER optimization of two configurations is shown, one where the channel under test (1553.7 nm) is surrounded by 50-GHz spaced neighboring channels and one where the channel spacing is increased to 200 GHz. A similar BER performance is observed for these two configurations and hence it can be concluded that as expected [18, 19], intra-channel FWM is dominant over inter-channel XPM, even at 50-GHz WDM channel spacing. The maximum feasible transmission distance in this experiment at the optimum input power (-7 dBm) was measured at 4,160 km for all 16 WDM 50-GHz spaced channels [1].

Discussion

A disadvantage of OFDM transmission system is the increased overhead resulting from training symbols, cyclic prefix and in some cases CPE pilot subcarriers. In [1], 40-Gb/s transmission is realized with a total 52.5-Gb/s nominal data rate (data rate before coding), hence a total overhead of 31.3%. However, in particular the overhead caused by cyclic prefix was large (15.6%). The cyclic prefix overhead can potentially be reduced by increasing the FFT size, e.g., when the FFT size is increased from 256 to 1024, the cyclic prefix overhead would be reduced from 15.6% to a mere 4.9%. The overhead of training symbols can be reduced by using either shorter training symbols or by increasing the training symbol spacing. With such techniques, the total overhead for OFDM modulation can realistically be reduced to about ~15%, slightly depending on the system configuration. Hence, OFDM modulation will normally have about double the overhead of what is required for single carrier modulation formats (7%), but at the advantage of creating a truly transparent modulation format that does not require any a priori knowledge about the transmission link.

6. Conclusion

In this paper coherent optical OFDM was discussed for long-haul fiber-optic transmission systems. Two important technologies were discussed: RF-aided phase noise compensation and PDM enabled by MIMO processing. Using these technologies, long-haul transmission of 52.5-Gb/s CO-OFDM is realized with 50-GHz channel spacing over 4,160-km of SSMF.

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