Improvement of Phase Noise Compensation for Coherent Optical OFDM via Data-Aided Phase Equalizer

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Abstract: We report a novel data-aided phase equalizer for coherent optical OFDM systems with RF-pilot enabled phase noise compensation. Simulation results corroborate the superior performance for different RF-pilot to signal power ratios.

OCIS codes: (060.4080) Modulation; (060.1660) Coherent communications

1. Introduction

Orthogonal frequency division multiplexing (OFDM) was originally designed for wireless transmission however, recently it has gained a great deal of attention in optical communications considering its ease of equalization and therefore robustness with respect to the fiber transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) [1]. A key feature of optical OFDM transmission systems is their capability to send pilot symbols (PSs) and pilot subcarriers which are known to the receiver to provide channel estimation. In optical OFDM, zero-forcing estimation method has been often used to extract the channel information and to calculate the equalization parameters [1,2]. For that, by comparing the received PSs with the transmitted PSs whose subcarriers are known, the channel information for each subcarrier can be easily obtained by a single complex division. To combat slight dynamic changes in channel characteristics, the PSs are periodically inserted into the OFDM data symbol sequence so that the channel estimation can be performed periodically. However, the laser phase noise needs to be tracked on a symbol-by-symbol basis. By using the pilot subcarriers that are inserted in every OFDM symbol, such a fast time variation of the channel can be compensated. In [3], Jansen proposed RF-pilot enabled phase noise compensation for OFDM systems while no extra optical bandwidth needs to be allocated. With this technique phase noise compensation is realized by placing an RF-pilot tone in the middle of the OFDM band at the transmitter that is subsequently used at the receiver to revert phase noise impairments. However, its accuracy is limited by noise; mainly coming from the accumulated spontaneous emission (ASE) noise of the erbium doped fiber amplifiers (EDFA) [2,3].

We recently proposed a data-aided adaptive weighted channel equalizer for direct-detection OFDM (DD-OFDM) transmission systems that could track slight drifts in the optical channel and allow the system to increase the periodicity of PSs and consequently to reduce the overhead [4]. In this paper, we introduce a novel data-aided phase equalizer (DAPE) for coherent optical OFDM (CO-OFDM) transmission systems and numerically demonstrate its capability to improve the precision of RF-pilot enabled phase noise compensation. DAPE updates the equalization parameters on a symbol-by-symbol basis and operates based on decision-directed channel estimation which is an alternative to the pilot-assisted channel estimation: it uses previous demodulator decisions to help estimate channel fading factors of the current symbol period. In decision-directed channel estimation, since the equalization parameters are not from pilot symbols, they are not as reliable, so the estimator's performance may suffer from error propagation. However, it does not require the overhead of the pilot-assisted estimators. To overcome the shortcomings of decision-directed and pilot-assisted channel estimators, we combine the two methods as suggested in [5], therefore, DAPE utilizes receiver decisions as well as pilot estimations and can produce better results when the receiver decisions are correct. Bit-error rate (BER) simulation results after transmission over 2000 km of uncompensated single-mode fiber (SMF) at 40 Gb/s show a significant improvement using DAPE. Alternatively, to achieve the similar BER, less RF-pilot power is required. The BER of 10^{-3}, for the received optical signal to noise ratio (OSNR) values of 16 and 13 dB, is achieved by 1 and 2.2 dB less RF-pilot power, respectively.

2. Theory of Operation

Assume n denotes the index for the received symbol (time index) and k is the index for the OFDM subcarrier (frequency index). The subcarrier-specific received complex value symbol, $R_{n,k}$, is equalized by applying a zero-forcing technique based on the previously estimated transfer factor, $\widetilde{H}_{n-1,k}$, that is taken as a prediction of the current channel transfer factor:

$$\hat{S}_{n,k} = R_{n,k} \Big/ \left(\widetilde{H}_{n-1,k} e^{j\Delta\varphi_{pilot,n}} \right) \tag{1}$$

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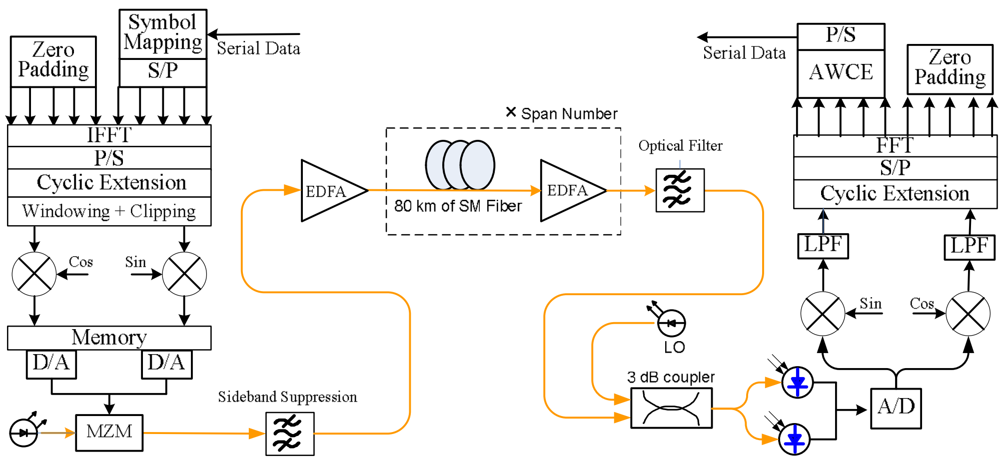

Fig. 1 - Simulation setup.

where $\hat{S}_{n,k}$ is the subcarrier-specific equalized complex value symbol and the term $\Delta\varphi_{pilot,n}$ is to compensate for the laser phase noise. $\Delta\varphi_{pilot,n}$ can be extracted by using RF-pilot [2,3] or pilot subcarriers [1]; however, in this paper, we focus on DAPE based on RF-pilot enabled phase noise estimation. $\hat{S}_{n,k}$, is then detected by the demodulator to make decision. Presuming that the decision was correct, the detected symbol, $\overline{S}_{n,k}$, can be further divided by the received symbol, $R_{n,k}$, in order to calculate a new channel transfer factor, $\hat{H}_{n,k}$:

$$\hat{H}_{n,k} = R_{n,k} / \overline{S}_{n,k} \tag{2}$$

We call this new channel transfer factor as the ideal channel transfer factor since if we knew it before demodulation and could apply it as the denominator in Eq. (1), then a perfect equalization and decision making would be achieved. $\hat{H}_{n,k}$ is basically the updated version of $\widetilde{H}_{n-1,k}$ and includes the information of the optical channel drifts in the time interval of the symbol number *n*. To suppress the receiver noise, a low-pass filter (LPF) is applied on $\hat{H}_{n,k}$. At this point, a more accurate estimation of the laser phase noise can be provided by averaging the difference between the phase term of the ideal channel transfer factor and the phase term of the previously estimated transfer factor over all subcarriers:

$$\Delta\varphi_{AWCE,n} = \sum_{i=1}^{N} \left(\arg\{\hat{H}_{n,i}\} - \arg\{\widetilde{H}_{n-1,i}\}\right) / N \tag{3}$$

where *N* is the total number of OFDM subcarriers including all data subcarriers. Now, $\Delta\varphi_{pilot,n}$ in Eq. (1) can be replaced by $\Delta\varphi_{AWCE,n}$ to provide a more accurate phase noise compensation and the new resulting $\hat{S}_{n,k}$ is again sent to the demodulator for better decision making. As we see in Eq. (3), since $\Delta\varphi_{AWCE,n}$ is calculated by averaging over all OFDM sub-channels, it is capable of suppressing the effect of ASE noise and therefore, providing a more accurate phase noise estimation. However, because the calculation of Eq. (3) is done after the demodulation and is dependent on Eq. (1), a fairly reliable RF-pilot enabled phase noise estimation is necessary to prevent error propagation. It is notable that since DAPE operates on a symbol-by-symbol basis and regarding the fact that OFDM symbol rate can be much lower than the actual bit rate, the implementation of DAPE does not necessarily require very high speed electronics. It is notable that since DAPE operates on a symbol-by-symbol basis and regarding the fact that OFDM symbol rate can be much lower than the actual bit rate, the implementation of DAPE does not necessarily require very high speed electronics.

3. Simulation of DAPE Performance in Long-Haul Transmission Systems

Fig. 1 depicts the simulated transmission link setup. Simulations are performed in MATLAB. The principle of operation of optical OFDM is well-known and the specific usage of each block diagram can be found elsewhere [1,2]. The original data at 40 Gb/s were first divided and mapped onto 1024 frequency subcarriers with QPSK modulation, and subsequently transferred to the time domain by an IFFT of size 2048 while zeros occupy the remainder. A cyclic prefix of length 350 is used to accommodate dispersion. Following this, an up-conversion stage shifts the OFDM signal to 10-30 GHz band. The OFDM signal is electrically up-converted using an electrical intermediate frequency (IF) carrier to modulate the signal upon applying a complex electrical I/Q mixer. To insert the RF-pilot in the middle of the OFDM signal for the phase noise estimation, we set the first OFDM channel to 0 and apply a small DC offset in I and Q tributaries of the IQ-mixer. In Fig. 2, the electrical spectrum after up-

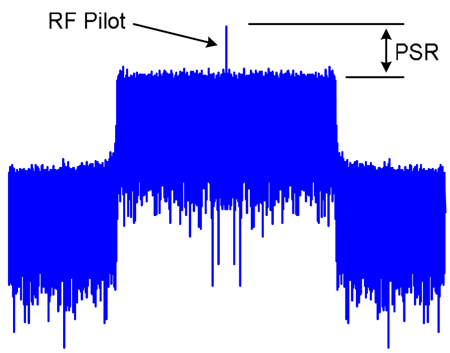

Fig. 2 - OFDM spectrum with RF-pilot enabled phase noise compensation.

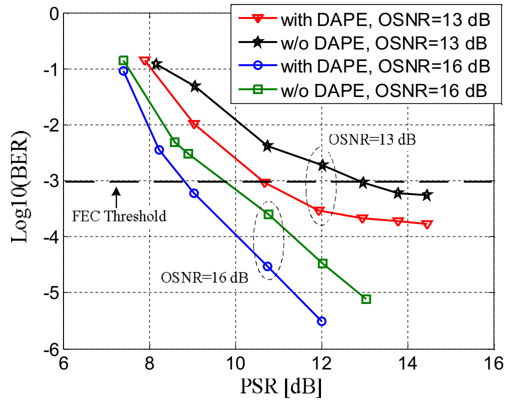

Fig. 3 – The BER performance of DAPE for two received OSNR values of 13 and 16 dB.

conversion is shown in which the RF-pilot can be seen. The ratio between the RF-pilot power and the signal power level is named as the pilot to signal power ratio (PSR) [2]. The resulting up-converted electrical OFDM data signal is then electro-optic converted using a chirp-less Mach-Zehnder modulator (MZM). Then the transmitted signal is optically filtered to suppress the sideband. Transmission link consists of 25 uncompensated SMF spans with dispersion parameter of 17 ps/nm.km, nonlinear coefficient of 1.5 $W^{-1}.km^{-1}$, PMD coefficient of 0.5 ps/√km and loss parameter of 0.2 dB/km. Spans are 80 km long and separated by EDFAs with the noise figure of 6 dB. Injected power to each fiber span is set to -4 dBm to limit the fiber nonlinearities. Split step Fourier method is used to simulate the optical fiber medium and by applying dynamic PMD model [6], the continuous time response of the channel is taken into account. 50 different random sets of time-domain realizations of laser phase noise and PMD have been simulated to mimic the continuous time characteristics of the optical channel. At the optical receiver, an optical filter with the bandwidth of 0.4 nm is applied to reject out-of-band ASE noise. The receiver is based on heterodyne CO-OFDM scenario in which the optical OFDM signal is converted into a real valued electrical OFDM signal at an IF and by using a subsequent electrical I/Q demodulator, the real and imaginary components are available in the baseband. In this simulation, each OFDM block consists of 2 pilot symbols and 62 data symbols (an overhead of 3% due to PS insertion).

Fig. 3 compares the BER performance versus PSR, with and without DAPE for two different received OSNR values of 13 dB and 16 dB. In both received OSNR cases, for lower values of PSR, DAPE slightly improves the performance however, as PSR increases, DAPE increases the precision of the phase noise estimation and therefore, better BER results are obtained. This is due to the fact that DAPE relies on the correct decision making and a fairly good RF-pilot enabled phase noise estimation is required to obtain a pronounced improvement. As one can see, to achieve the forward-error-correction (FEC) threshold, DAPE requires 1 and 2.2 dB less RF-pilot power for the received OSNR values of 16 and 13 dB, respectively, showing higher improvement for the noisier scenario.

4. Conclusion

We reported a novel data-aided phase equalizer to improve the RF-pilot enabled phase noise compensation for CO-OFDM transmission systems and numerically studied its performance for a 2000 km uncompensated link at 40 Gb/s. Combining the RF-pilot enabled and the data-aided equalizers for phase noise compensation improves the received signal quality as the BER simulations demonstrate its superior performance. Alternatively, the BER of 10^{-3} for the received OSNR values of 16 and 13 dB can be achieved by 1 and 2.2 dB less RF-pilot power, respectively.

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