Fiber Nonlinearity Mitigation in 428-Gb/s Multiband Coherent Optical OFDM Systems

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Abstract: We propose DFT-spread (DFT-S) OFDM within each sub-band of multiband-CO-OFDM to mitigate fiber nonlinearity. For 1000-km standard-single-mode-fiber transmission at 420-Gb/s, 32-band DFT-S CO-OFDM outperforms conventional CO-OFDM and coherent single-carrier by 1.1 and 0.8 dB, respectively.

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1. Introduction

The relentless growth of internet traffic has spurred intense research and development of transmission systems over 100 Gb/s [1-5]. Coherent optical OFDM (CO-OFDM) is one of the attractive modulation formats for 100 Gb/s and beyond. It has demonstrated extreme robustness against fiber chromatic dispersion and polarization mode dispersion (PMD) [3-5], and there has already been some research activity looking at even faster transmission rate, such as 400 Gb/s and at 1 Tb/s using CO-OFDM [6-7]. However, one of the major obstacles of achieving these next-generation transport systems is the electronic signal processing bandwidth required, e.g., about 60 GHz for 400 Gb/s systems, which is difficult to realize in the foreseeable future on CMOS ASICS platform. The concept of multiband CO-OFDM has been proposed to divide the entire OFDM spectrum into multiple orthogonal bands, thereby resolving this electronic bottleneck [3-4]. These multiple OFDM bands with small or zero frequency guard bands can be multiplexed and de-multiplexed without interference due to inter-band orthogonality [4]. The other intrinsic disadvantage of CO-OFDM is that OFDM generally suffers from high peak-to-average power ratio (PAPR), which results in high nonlinearity in transmission. Fiber nonlinearity mitigation in CO-OFDM systems has therefore become an important research topic [8-10]. Nevertheless, most of the reports proposed for CO-OFDM apply equally well to the single-carrier coherent systems [8-10], and thus do not take advantage of the unique multicarrier nature of CO-OFDM format. In this paper, we propose a novel nonlinearity mitigation approach making use of the existing multiband structure of CO-OFDM. In particular, each subband is filled with a discrete-Fourier-transform-spread OFDM (DFT-S OFDM) signal that reduces the PAPR within each subband. This, in return, improves the overall nonlinearity transmission performance. DFT-S OFDM has been used in wireless communications to realize single-carrier frequency-domain equalization (SC-FDE), and has already been incorporated into the uplink of the next generation 4G mobile standard, known as long-term-evolution (LTE) [11-12]. For its application to the fiber optic channels in this paper, the functionality of OFDM is two-fold: (i) OFDM frames are used to fill the single-carrier-like spectrum within each sub-band, and (ii) OFDM helps maintain the orthogonality between the neighboring bands, and subsequently avoids inter-band crosstalk. Simulations show that for 428-Gb/s multi-band CO-OFDM systems, the optimal sub-band bandwidth for DFT-S OFDM is about 3-12 GHz. Furthermore, the Q factor of DFT-S OFDM outperforms conventional OFDM and single-carrier coherent systems by 1.1 and 0.8 dB respectively for 1000-km SMMF fiber transmission without optical dispersion compensation. This finding signifies that multiband DFT-S CO-OFDM may overcome the inherent nonlinearity disadvantage associated with conventional CO-OFDM systems, and, in fact, may have slight nonlinearity benefits over single-carrier coherent systems.

2. Principle of nonlinearity mitigation in multiband DFT-S CO-OFDM systems

It is well-known that the PAPR of CO-OFDM signal greatly affects its nonlinearity performance for low-rate systems [8-10]. It is therefore sensible to use PAPR reduction algorithms at the transmitter to mitigate the nonlinearity impact [13-14]. However, for high-rate systems such as 400 Gb/s, the fiber dispersion plays critical roles, inducing fast walk-off between subcarriers [10]. The PAPR of such becomes a transient value during transmission due to fiber link dispersion, thereby rendering the PAPR reduction at the transmitter ineffective. In contrast, if the PAPR mitigation approach is performed on a subband basis, and due to the fact each subband has a much narrower bandwidth, the signal within each sub-band can be relatively undistorted over relatively long distances. This results in less inter-band and intra-band nonlinearity. In a nutshell, PAPR reduction on sub-band basis will be more effective than that across the entire OFDM spectrum. It is also natural to predict there is a ‘sweet spot' of sub-band bandwidth within which the PAPR mitigation should be performed: On one hand, if the subband bandwidth is too broad, as was just argued, the PAPR reduction will not be effective due to the fiber dispersion. On the other hand, if the sub-bands are too narrow, the neighbouring bands interact just as narrowly-spaced OFDM subcarriers, generating large inter-band crosstalk due to narrow subband spacing and incurring a large penalty.

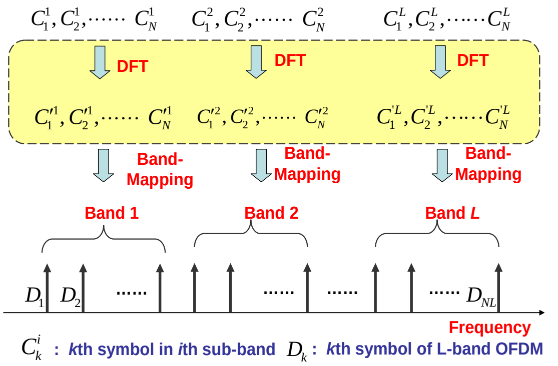

Figure 1. Conceptual diagram of multiband DFT-spread OFDM. Operations in the shaded box are omitted for conventional OFDM.

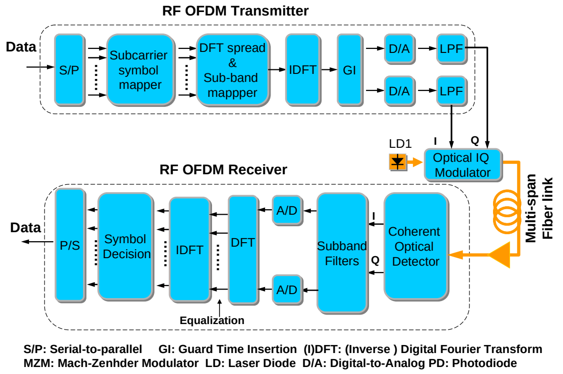

Figure 2. Simulation Configuration of 428-Gb/s multiband DFT-S CO-OFDM systems.

There are various ways to perform PAPR reduction such as selective mapping [13] and active constellation extension [14]. We here adopt DFT-S OFDM due to its low computational complexity and compatibility with the OFDM frame structure. Fig. 1 shows the conceptual diagram of subcarrier mapping of multi-band DFT-S CO-OFDM. It is instructive to compare the generation of DFT-S OFDM with conventional OFDM. For simplicity, we study the transform and mapping for one subband. The time-domain sample of conventional OFDM is given by

$$x_m = \sum_{k=0}^{N} C_k e^{j\frac{2\pi}{N}(k-1)(m-1)} \tag{1}$$

where x_m is the mth time-domain sample, C_k is the kth frequency-domain symbol, N is the number of DFT points. For DFT-S systems, instead of directly applying the IDFT to convert the frequency-domain symbol C_k to time-domain symbol x_m , the original N symbols first go through DFT spreading, namely, a new set of N symbols C'_k are generated given by

$$C'_k = \sum_{l=1}^{N} C_l e^{-j\frac{2\pi}{N}(k-1)(l-1)} \tag{2}$$

The new N symbols C'_k are then mapped onto M-point DFT symbol vector $\boldsymbol{D}$ (Fig. 1), for instance, from the (K_1+1)th to (K_1+N)th position, where K_1 is the starting position of band mapping. The time-domain DFT-S OFDM signal for this subband signal is thus expressed as

$$x_m = \sum_{k=K_1+1}^{K_1+N} D_k e^{j\frac{2\pi}{M}(k-1)(m-1)}, \qquad D_k = C'_{k-K_1} \tag{3}$$

where $M = L \cdot N$ and L is the number of subbands. The effectiveness of the PAPR reduction of DFT-S OFDM can be better appreciated if we study the special case of M=N, K_1=0 in (3). We would have the time-domain signal x_m equal to OFDM symbol C_k (essentially, single-carrier modulation). Subsequently, we expect that the PAPR of DFT-S OFDM will be significantly improved over conventional OFDM [11-12]. In the proposed multiband DFT-S OFDM, after DFT spreading, the new DFT-S symbols from all the bands will be mapped to L groups of consecutive subcarriers, and the summation in (3) will extend from 1 to M. The receiver process is the reverse of (2) and (3).

3. Simulation of 428-Gb/s multiband DFT-S OFDM transmission

We have performed simulations to assess the nonlinearity-mitigation capability of the proposed multiband DFT-S OFDM transmission. The simulated system is shown in Fig. 2. Dual-polarization transmission is used in the simulation, but not shown in Fig.2. In the transmitter, there is an extra DFT for DFT spreading, and at the receiver, there is an extra IDFT to rewind the spreading. Therefore, there is a computational complexity penalty for using DFT-S OFDM. However, compared to all other PAPR reduction algorithms, it has the least complexity. Moreover, considering its nonlinearity-mitigation capability, DFT-S OFDM has proven to be worthwhile in wireless communications [15]. The IDFT at the transmitter should be performed with mixture of electrical and optical combiners in practice [3-4]. The sub-band filters at the receiver can be implemented using electrical, optical or digital filters. The simulated transmission parameters are: fiber length of 100 km per span, D_{SSMF}=16 ps/nm/km, α_{SSMF}=0.2 dB/km, γ_{SSMF} =1.3 $w^{-1}km^{-1}$, noise figure of optical amplifiers of 6 dB, three WDM channels with 140-GHz channel spacing, 64 number of subcarriers in each subband when the number of subbands is over 32. For fair comparison, we use a 1/8th cyclic prefix ratio for all the cases. This requires the number of subcarriers per subband to scale up in order to increase the absolute length of cyclic prefix when the number of subbands decreases below 32. We first find the optimal number of subbands, or equivalently, the optimal subband bandwidth for 428-Gb/s multiband CO-OFDM signal. Fig. 3 shows the Q performance at an input power of 7 dBm for single-wavelength 428-Gb/s multi-band DFT-S OFDM transmission. It can be seen that the optimal number of bands is close to 16, but 8 and 32 have very similar performance. Because larger number of subbands reduces the cyclic prefix requirement and facilitate finer bit loading on subband basis, we therefore choose 32 subbands for simulation in the remainder of the paper, if not otherwise specified. This corresponds to 3.77 GHz subband bandwidth. It is noted that the number of subcarriers in each subband is not an important factor in nonlinearity performance for multiband DFT-S OFDM systems, since the subcarriers in each subband are merely used to contain the same 'single-carrier' spectrum.

Detailed simulations are carried out, and we compare performance between three systems: (i) multiband (32-band) DFT-S OFDM, abbreviated as 'MB-DFT-S-OFDM', (ii) a single-carrier coherent system, abbreviated as 'SC', which is a special case of one-band DFT-S OFDM (its performance should be completely identical to the single-carrier coherent systems generated directly in time-domain with a Nyquist bandwidth) and (iii) 32-band conventional OFDM, abbreviated as 'MB-C-OFDM', where there is no DFT-spreading performed. For fair comparison, all three systems occupy the same bandwidth of 120 GHz, and use the same cyclic prefix ratio of 1/8. In the case of single-carrier systems, due to relatively large bandwidth, the absolute length of the cyclic prefix required is relatively long, implying long block lengths. But this is not a problem because the single-carrier is robust against a laser linewidth of 100 kHz. Figs. 4 (a) and (b) show the Q factor as a function of the launch power for MB-DFT-S-OFDM, SC, and MB-C-OFDM systems, respectively, for both single-channel and 3-channel WDM transmission. For the single channel (WDM) systems, the optimal launch powers are 7(6), 6(5), and 6(5) dBm for MB-DFS-OFDM, SC, and C-OFDM respectively, signifying the nonlinearity performance enhancement for MB-DFS-OFDM systems over either SC or MB-C-OFDM systems. As a result, for single channel (WDM), the optimal Q factors for MB-OFS-OFDM are improved by 0.6(0.8), and 1.2(1.1) dB over SC and MB-C-OFDM systems, respectively.

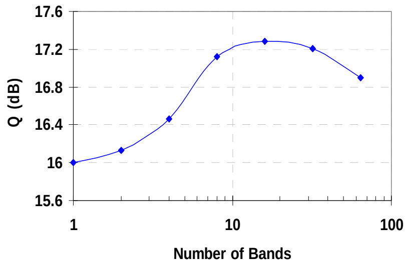

Fig. 3 Q factor as a function of number of bands at 7-dBm launch power with 428-Gb/s single channel transmission.

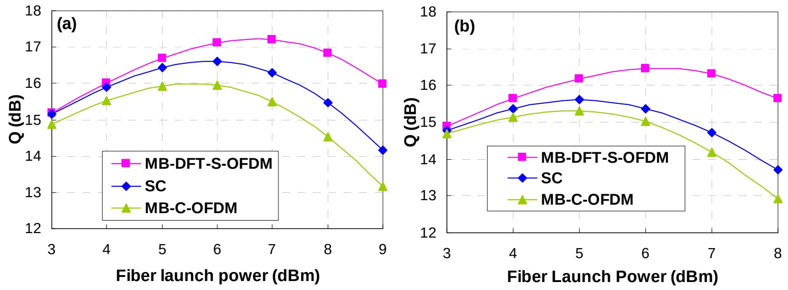

Fig. 4 Q factor as a function of fiber launch power for MB-DFT-S-OFDM, SC, and MB-C-OFDM for both (a) single channel and (b) 3-channel WDM transmission.

4. Conclusions

We have proposed DFT-spread (DFT-S) OFDM within each sub-band of CO-OFDM to mitigate fiber nonlinearity. For 1000-km SSMF transmission, 3x428-Gb/s WDM DFT-S CO-OFDM outperforms conventional CO-OFDM and coherent single-carrier systems by 1.1 and 0.8 dB, respectively.

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