Flexible Transceivers Using Adaptive Digital Signal Processing for Single Carrier and OFDM

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Abstract: Advanced DSP algorithms for channel estimation and equalization, carrier phase recovery and nonlinearity mitigation for flexible transceivers are discussed for both single carrier and OFDM systems.

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1. Introduction.

As the 100 G optical transport has been commercialized and under deployment, interests are moving to next generation transmission systems with higher data rate per channel (e.g. 400 Gb/s and 1 Tb/s) and higher spectral efficiency in order to satisfy the ever-increasing capacity demand [1]. Elastic optical networks have been proposed as an approach to improving the spectral efficiency where dynamic traffic and varying link conditions occur [2]. Flexible transceivers are a key element in elastic networks, and they are expected to be data rate-adaptive, distance-adaptive and bandwidth-adaptive [3]. Transceivers with flexible modulation format [4], flexible bandwidth based on superchannels [5], and adaptive forward error correction (FEC) coding rates [6] have been proposed and demonstrated. In such transceivers with coherent detection, adaptable digital signal processing (DSP) algorithms are crucial in order to optimize computational resources and achieve good performance.

In this paper, we review some DSP algorithms proposed in our recent work which are adaptable to modulation format and therefore suitable for flexible transceivers. For single carrier systems, a pilot symbol aided phase locked loop (PLL) with superscalar parallelization was proposed to achieve a very high laser linewidth tolerance for arbitrary QAM format with reasonably low complexities [7]. In addition, we proposed the use of the RF-pilot to jointly compensate for fiber nonlinearities and laser phase noise for single carrier systems [8, 9]. For the purpose of ultra-fast and low overhead polarization demultiplexing and channel equalization, we proposed a training symbol based approach [10]. Finally, we present a demonstration of time domain hybrid QAM transmission with adaptive data rates [11]. In the second part of this paper, we discuss CO-OFDM systems, which usually employ data-aided DSP algorithms, and therefore are inherently format-flexible. We analyzed the effect of laser phase noise and its compensation in reduced-guard-interval (RGI) CO-OFDM [12-14]. In addition, we proposed and demonstrated a zero-guard-interval (ZGI) CO-OFDM transmission with a novel equalization scheme [15, 16].

2. Adaptive DSP algorithms for flexible single carrier systems.

Carrier phase recovery (CPR) is an indispensable procedure for coherent single carrier receivers to accommodate the effect of laser phase noise. We proposed a pilot symbol aided PLL with superscalar parallelization (denoted as SSP-PLL) [7]. This CPR algorithm is suitable for parallel processing and is modulation format-independence. In addition, it achieves a laser linewidth tolerance as high as the well-known blind phase search (BPS) algorithm, but reduces the computational complexity by a factor of >10 compared to BPS. The basic idea of SSP-PLL is to use a large buffer to store the input symbols and re-arrange them in order to have consecutive symbols in each parallel channel for the PLL processing. Since the feedback delay is significantly reduced, a high laser linewidth tolerance can be achieved [17]. Pilot symbols are required to initialize the PLL for each block, and we proposed a novel superscalar structure to reduce the pilot overhead. We also showed that differential coding can be removed in this scheme, leading to a performance improvement. Furthermore, a second stage maximum-likelihood (ML) phase estimation is added to compensate for the performance degradation caused by any residual feedback delay. The performance of SSP-PLL was demonstrated in QPSK, 16-QAM and 64-QAM experiments and the complexity was discussed in our previous work [7].

The RF-pilot technique was first employed in CO-OFDM systems to combat laser phase noise-induced inter-carrier interference (ICI) [18]. Later, it was shown that it can also be used to compensate for both intra-channel and inter-channel fiber nonlinearities [19]. We borrowed this technique from single carrier systems with the availability of digital-to-analog converters (DACs) [8, 9]. Pilot tone insertion is enabled by single-sideband (SSB) subcarrier
modulation of both I and Q baseband signals in the DSP domain. At the receiver, a low pass filter is used to filter out the RF-pilot, which carries the same phase noise experienced by data signals, to do phase noise compensation. The mathematical description and numerical study of this approach for carrier phase recovery was presented in [9]. The high laser linewidth tolerance comparable to other CPR algorithms known in literature was demonstrated. Moreover, the capability of the nonlinearity compensation of the RF-pilot in single carrier systems was demonstrated in [8] by simulation for both QPSK and 16-QAM formats.

A time domain 2-by-2 butterfly filter is needed in single carrier systems to demultiplex the polarization and equalize the residual linear effects. An adaptive algorithm such as constant modulus algorithm (CMA) and least mean square (LMS) are normally applied for the filter taps convergence and channel tracking. However, thousands of symbols might be required in the worst scenario for the taps convergence, leading to a large overhead. In [10], we proposed a training based ultrafast channel estimation suitable for any modulation format. The proposed scheme is based on the fact that modern fibers have very small PMD parameter (< 0.1 ps/km<sup>1/2</sup>), and therefore the main effect is the polarization rotation which could be estimated using tens of training symbols. Then the estimated matrix entries are used to set the initial center taps of the butterfly equalizer. As polarization crosstalk is mitigated, the signal quality is high enough for the decision-directed (DD) steady-state adaptation. The performance of our approach was demonstrated in 112 Gb/s PDM-QPSK and 224 Gb/s PDM-16QAM experiments.

More recently, we demonstrated a rate-adaptive transmission of time domain hybrid QAM format [11]. By interleaving the different QAM formats, e.g. QPSK, 8-QAM and 16-QAM, we successfully realized a “continuous” tradeoff between spectral efficiency and transmission distance. A format-independent DSP aided receiver for such hybrid QAM transmission was also proposed. Two experiments were conducted: 1) 28 Gbaud non-return-to-zero (NRZ) transmissions with data rates from 112 Gb/s to 224 Gb/s and corresponding distances from 6400 km to 1050 km. 2) A superchannel transmission, achieving “continuous” data rates from 576 Gb/s to 1.15 Tb/s, spectral efficiencies from 3.84 b/s/Hz to 7.68 b/s/Hz, and transmission distances from 5540 km to 470 km.

3. Adaptive DSP algorithms for flexible CO-OFDM systems.

Because of the data-aided DSP, CO-OFDM is inherently suitable for flexible transceivers. However, conventional CO-OFDM needs a large overhead for channel equalization and data recovery. RGI CO-OFDM, which compensates for chromatic dispersion (CD) via an overlapped frequency domain equalizer (OFDE) prior to OFDM demodulation, was later proposed to reduce the cyclic prefix (CP) overhead (e.g. down to 3%) and also improves the performance by optimizing the fast Fourier transform (FFT) size [20]. Based on the structure of the RGI CO-OFDM, we proposed a ZGI CO-OFDM using a novel equalization scheme to completely remove the CP from data symbols [15]. In particular, it uses the channel transfer function estimated from OFDM channel estimation to update the coefficients of the OFDE, and thus enables the OFDE to compensate for not only CD but also residual linear effects. Compared to the RGI CO-OFDM, the extra complexity added was shown to be reasonably low [15]. The experimental demonstration of ZGI CO-OFDM transmission with 28 Gbaud QPSK and 16-QAM formats was reported in [16].

Conventionally, CO-OFDM is considered to be vulnerable to laser phase noise-induced ICI and thus requires narrow linewidth lasers such as external cavity laser (ECL). Using RGI (or ZGI) CO-OFDM significantly reduces the ICI since the symbol duration can be much shorter. However, the dispersion-enhanced phase noise (DEPN), which is the interaction between CD and phase noise from local oscillator (LO), puts a limit on the linewidth tolerance [12, 14]. To be specific, due to the CD-induced walk-off different subcarriers within each OFDM symbol will experience different phase shift from the LO. Therefore, there exists residual phase shifts resulting in a non-negligible performance loss if we still apply the conventional common phase error compensation. The analytical study of DEPN can be found in [14] and the experimental demonstration was reported in [12]. In order to cope with DEPN, we proposed the concept of intra-symbol carrier phase recovery (IS-CPR) [13]. Particularly, the CPR algorithms designed for single carrier systems such as ML phase estimation and PLL can be applied to each OFDM symbol to recover the phase, since the statistics of DEPN is similar to a Wiener process.

4. Conclusion

We reviewed and discussed the digital signal processing (DSP) algorithms proposed in our recent work, which are suitable for flexible transceivers in future elastic optical network. The algorithms are mainly for channel estimation and equalization, laser phase noise compensation, and fiber nonlinearity mitigation for both single carrier and OFDM systems.

References