Beyond 100 Gb/s: Advanced DSP Techniques Enabling High Spectral Efficiency and Flexible Optical Communications

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Abstract: We discuss recent advances in DSP techniques for long-haul systems beyond 100Gb/s as well as adaptive transmissions supporting software-defined flexible transponders and Elastic Optical Networks(EON).

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1. Introduction

Over the past decade, advances in optical hardware such as external modulators, narrow-linewidth lasers and 90 degree hybrids allow Digital Signal Processing (DSP) algorithms from wireless/copper-wire communications [1] to be applied in optical communications and enable the current success of long-haul coherent systems. Basic DSP units such as chromatic dispersion(CD) compensation, polarization-mode dispersion (PMD) compensation, timing phase recovery, frequency offset compensation as well as carrier phase estimation (CPE) have formed the standard DSP platform in commercial coherent receivers. Moving forward, 400 Gb/s and 1 Tb/s per-channel transmission using 16-QAM and above are demonstrated and beginning to be commercialized in 2012. The next wave of advances is envisioned to be Elastic Optical Networks (EON) in which dynamic and programmable software-defined transmissions adapt to network conditions to maximize overall efficiencies. One of the key challenges therein is adaptive/flexible receiver DSP supporting multiple bit rates, bandwidth and/or different modulation formats. In this article, we will review the latest DSP developments for optical transmissions beyond 100 Gb/s and discuss on-going efforts to realize adaptive DSP platforms for future EON.

2. Carrier Phase Estimation(CPE) for 16-QAM systems and beyond

Unlike wireless systems, oscillator phase noise (laser phase noise) is a major impairment in optical transmissions and its effect grows with modulation order. Therefore, CPE is an important DSP block in 16-QAM systems and above. After preceding DSP that compensate other impairments and down sampled to symbol rate, let the k^{th} symbol in one polarization going into the CPE unit be $r_{CPE}(k) = s(k)\cdot e^{j\phi(k)} + z(k)$ where $\phi(k) = \phi_t(k) + \phi_r(k)$ is the combined transmitter and receiver phase noise and $z(k)$ is the additive ASE noise. In radio communication systems, phase synchronization is typically achieved by a phase-lock loop (PLL) employing a one-tap least-mean square (LMS) filter to implement decision-directed phase estimation in a feedback manner. Feedback techniques rely on calculating the phase estimate $\phi(k)$ from $r_{CPE}(k)$ and the symbol decision $\hat{s}(k)$ and use it as the initial estimate for $\phi(k+L)$ where L denotes the total feedback delay. L is determined by the degree of parallelization P and pipelining (number of steps in an algorithm). Unfortunately in high-speed optical communications, required ASIC parallelizations may create large feedback delays and considerably limit the performance of feedback algorithms. One would either need feedforward algorithms avoiding feedback loops or develop intelligent algorithmic and hardware structures that can somehow reduce P and/or L.

For feedforward CPE, the Viterbi-Viterbi Phase Estimation (VVPE) [2] is the most commonly used for QPSK systems. For higher-order modulation, the most widely known feedforward CPE is blind-phase-search(BPS) [3]. BPS originates from general synchronous communication systems and the basic idea is to rotate the input signals by M test carrier phase angles $\xi_m = \frac{m-1}{M}\cdot\frac{\pi}{2}, m \in \{1,2,...,M\}$. Then, for a given ξ_m, one computes the squared distance between the rotated symbols and their closest constellation point over $2N$ consecutive symbols as an error

$$e_m = \sum_{n=k-N}^{k+N} \left| r_{CPE}(n)\exp(-j\xi_m) - \Gamma\left(r_{CPE}(n)\exp(-j\xi_m)\right) \right|^2 \quad (1)$$

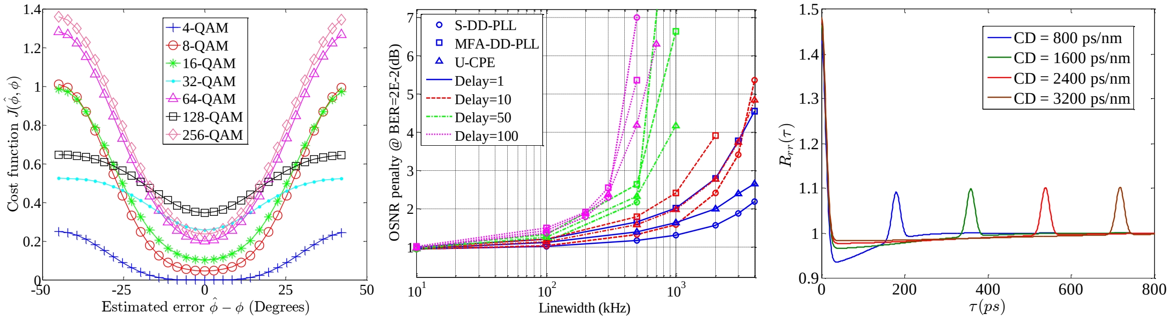
where $\Gamma(\cdot)$ denotes decision. Subsequently, the phase noise is estimated by searching for the phase ξ_m that minimizes e_m. BPS is blind, feedforward, applicable to arbitrary QAM formats but it has huge algorithmic and hardware complexity. Such complexity can be somewhat lowered by reducing the number of 'test phases' using multi-stage approaches[4]. Alternatively, the signals in the inner and outer circle of a 16-QAM constellation can actually be used in the standard VVPE as a coarse phase estimate. Identifying these symbols for VVPE is known as QPSK partitioning [5]. A second-stage of maximum likelihood (ML) phase estimate can further refine the estimation accuracy. The overall QPSK partitioning + ML technique performs similarly with single-stage BPS while the computation complexity can be reduced by a factor of five [6]. Various aspects of QPSK partitioning can be optimized to further reduce complexity and improve linewidth tolerance. However, it should be noted that for even higher-order formats such as 64-QAM, single- or two-stage BPS based-algorithms are still more advantageous and feasible at this point.

3. DSP developments for flexible transponders and Elastic Optical Networks

It is envisioned that future Internet traffic will be much more dynamic, unpredictable and heterogeneous in all aspects due to the emergence of data centers and other large content providers with dynamic traffic demands across optical networks. Consequently, flexible/adaptive transmissions or elastic optical networking (EON) that maximize network efficiency have attracted a lot of attention recently [7]. To this end, advances in impairment-aware network layer routing and spectrum assignment protocols, flexible ROADMs enabling a switching granularity of 3.125 GHz have laid down the fundamental building blocks for EON. In terms of the physical layer, we would favor a universal software-defined transceiver that can accommodate different bit rates, symbol rates, modulation format, coding and/or path of transmission across the network. Another imperative feature for such flexible receivers is rapid and robust physical channel estimation for EON.

At present, DSP for receiver front-end corrections, CD compensation and TPR are essentially modulation format independent while CPE, FOE and adaptive signal processing for compensating PMD and other transceiver imperfections are somewhat modulation format dependent. For CPE, it can be argued that the BPS architecture is applicable to all modulation formats but similar to the majority of feedforward CPE techniques, BPS still requires a-priori knowledge of the modulation format to compute the phase estimate. To facilitate a blind and modulation-format-independent or universal-CPE (U-CPE), one seeks a cost function common to all modulation formats that is optimized when the phase estimate $\hat{\phi}$ approaches the true laser phase ϕ. For practical modulation formats, maybe the only common characteristic is that their constellation is somewhat square-shaped. We make use of this insight [8] and study the real and imaginary part of the CPE input $r_{CPE}(k)$ in a single polarization and consider the cost function

$$J\left(\hat{\phi},\phi\right)=\mathbf{E}\left[\left(\left(\mathrm{Re}\left\{r_{CPE}(k)e^{-j\hat{\phi}}\right\}^{2}-0.5\right)^{2}+\left(\mathrm{Im}\left\{r_{CPE}(k)e^{-j\hat{\phi}}\right\}^{2}-0.5\right)^{2}\right)^{2}\right]. \qquad (2)$$



(a) (b) (c)

Fig. 1. (a) Cost function $J(\hat{\phi},\phi)$ (without ASE noise) vs. phase estimation error $\hat{\phi}-\phi$ for different modulation formats. (b) OSNR penalty vs. laser linewidth for 32GBaud PM-16-QAM systems using standard S-DD-PLL, U-CPE and MFA-DD-PLL at SD-FEC threshold of 2E-2, corresponding to a OSNR of 16.8 dB. (c) The auto-correlation function of received power waveform $R_{rr}(\tau)$ for 112 Gb/s PM-QPSK systems with 800, 1600, 2400 and 3200 ps/nm of CD. The peak location can be used to determine link CD and is insensitive to laser impairments, ASE noise and first-order PMD effects.

As shown in Fig. 1(a), $J(\hat{\phi},\phi)$ is minimized at $\hat{\phi}-\phi=0$ regardless of modulation format, thus illustrating its suitability as a cost function for U-CPE. We compare U-CPE with 1) standard decision-directed phase lock loop (S-DD-PLL) in which the modulation format is known for symbol decision and 2) modulation format agnostic (MFA)-DD-PLL in which QPSK is assumed in the DD-PLL irrespective of the actual signal modulation format. The OSNR penalties with different linewidths and feedback delays are shown in Fig. 1(b) for 32GBaud/s PM-16-QAM systems. U-CPE performs closely with DD-PLL and considerably outperforms MFA-DD-PLL. In fact, U-CPE performs the best when the delay is large. For practical ECL linewidths of 100kHz, U-CPE at most induces a 0.35dB penalty for

16- and 64-QAM signals compared with standard DD-PLL but U-CPE has the advantage that it is completely blind and also converges faster than S-DD-PLL.

Another important feature of an EON is rate-adaptive transmissions. Conventional transponders employ individual modulation formats such as BPSK, QPSK or 16-QAM which have discrete spectral efficiencies and achievable transmission distances, resulting in limited flexibility that hinders overall network efficiencies. One approach to realize full flexibility in bit rates and/or spectral efficiencies is time domain hybrid QAM (TDHQ) [9]. This is accomplished by interleaving two different modulation formats in the time domain and their relative ratio of occurrence determines the overall spectral efficiency and hence maximal reach. Recently, Zhuge et al. conducted 28 Gbaud non-return-to-zero (NRZ) experiments using various combinations of two QAM formats including QPSK, 8QAM and 16QAM and realize a continuous range of data rates from 112 Gb/s to 224 Gb/s. The measured maximum reach at a BER of 4.6×10-3 (7% hard-decision forward error correction (FEC) threshold) ranges from 6400 km to 1100 km and varies smoothly with the number of bits/symbol (or spectral efficiency). The experiment demonstrates that TDHQ can be used to maximize spectral efficiencies for different link conditions in an EON. Moreover, no extra hardware is required with respect to a conventional digital-to-analog converter (DAC) based-flexible transmitter.

Enabling dynamic lightpath provisioning and automatically switched optical networks (ASON) will require a digital coherent receiver to quickly estimate the physical layer conditions of the channel. In principle, parameters such as link CD and PMD can be estimated using blind adaptive equalization techniques. However, for 28-32 Gbaud signals, adaptive equalizer can handle around ±200 ps/nm residual CD beyond which it will take too long to converge or may simply not converge at all. Therefore, separate efforts for CD estimation prior to data transmission are to be in place. CD can be estimated by inserting training symbols or specific bit sequences [10] but the length of pilot symbols needs to grow with CD and may become prohibitive for links approaching 100,000 ps/nm of CD. On the other hand, blind non-data aided (NDA) CD estimation is often required/preferred [11] for equalizer initialization but they need to be insensitive to other impairments, independent of modulation formats and needs to be fast. To this end, we proposed to use the auto-correlation of received signal power waveform [13]

$$R_{rr}(\tau) = \mathbf{E}\left[\left(\left|E_{r,x}(t)\right|^2 + \left|E_{r,y}(t)\right|^2 \right) \cdot \left(\left|E_{r,x}(t+\tau)\right|^2 + \left|E_{r,y}(t+\tau)\right|^2 \right) \right] \qquad (3)$$

where $E_{r,x(y)}(t)$ denotes the received signal in the *x-(y-)*polarization. Due to CD-induced inter-symbol interference, Fig. 1(c) shows that $R_{rr}(\tau)$ exhibits a peak whose location is analytically shown to depend on accumulated CD only and is independent of amplifier noise, laser frequency offset, laser phase noise, first-order PMD and modulation format. Thus, the peak location can be used as a fast and robust CD estimation technique. The peak in $R_{rr}(\tau)$ become less apparent for NRZ and Nyquist shaped signals but additional high-pass filtering to the received signal can 'preserve' the peak and ensure robust CD estimation. It should be noted that most of the proposed CD estimation techniques can be seen as different variants of calculating the CD induced-group delay between the upper-side-band and lower-side-band of the received signal and estimation accuracies will suffer for Nyquist shaped signals with sharp spectral roll-off.

4. Conclusions

Digital coherent receivers are well-proven technologies that define the current generation of 100 Gb/s transmission systems. We are witnessing another era of DSP developments for higher spectral efficiency as well as flexible/adaptive transmissions. Research on adaptive transponders supporting and maximizing throughput under a wide set of network conditions will become a major focus area in digital coherent communications in the near future.

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