Joint Optimization of Phase Retrieval and Forward Error Correcting for Direct Detection Receiver

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Abstract *We have experimentally demonstrated that performance of a phase retrieval (PR) receiver in optical systems can be significantly improved by a joint optimization of PR pilots overhead and FEC coding overhead, enabling a higher data rate and upto 66% reduced number of PR iterations.*

Introduction

Coherent optical communication is becoming a compelling solution for short-reach high-capacity optical interfaces such as inter/intra- datacenter interconnects and metro networks for its capability to reconstruct the full field of optical signals. However, coherent detection is considered a costly and complex solution, especially in advanced spatial-division-multiplexing (SDM) systems. A practical optical coherent transceiver requires low-cost, energy efficient and compact solutions, which means the simplification of the optical coherent front-end via digital signal processing is preferable.

To simplify the receiver architecture, many receiver schemes using only direct detection, e.g. the Kramers-Kronig (KK)[1] and Stokes vector receiver[2]. However, an optical carrier is needed in both schemes. To achieve a cost-efficient and flexible coherent transceiver solution, phase retrieval (PR) solution was proposed in optical fiber communication. By using PR, the use of optical carrier in above-mentioned receiver schemes can be eliminated. Instead, multiple magnitude-only measurements with different linear projections are needed to avoid phase ambiguity. Recently, a PR-based coherent receiver using two-dimensional photodetector array was experimentally demonstrated, which can support polarization-multiplexed complex signal transmission[3]. A modified Gerchberg-Saxton (GS) algorithm was proposed to realize polarization- and mode-multiplexed full-field reconstruction based on chromatic dispersive elements[4],[5]. In the previous studies, it is shown that one additional projection plane is sufficient to retrieve the phase of polarization-multiplexed 30-Gbaud quadrature phase shift keying (QPSK) signal with the aid of enough pilot symbols[4]. The following studies shows that more projection planes provide faster and better convergence[6].

In the scenario of high speed optical communication systems with low-cost and energy efficient requirements, it is also important to optimize the forward error correction (FEC) codes in order to maximize the net data rates and increase the transmission distance. One of the key assumptions of FEC input is that the signal is converged to a high retrieved phase accuracy after PR algorithm. But it requires the variation of overhead (OH) and iterations. For example, signal with the aid of enough pilot symbols, which potentially could achieve better performance, could have worse performance than signal with less pilot symbols when not having enough iterations[4],[5]. This is due to the fixed FEC OH assumption, which may has inadequate capability for error correcting. Such effect should have higher impact in inadequate PR pilots cases. Therefore, it is still not clear whether PR and FEC can be jointly beneficial in complexity-limited scenarios, since it requires a detailed study to optimize the different parameter choices.

In this work, we investigate a joint optimization of PR and FEC parameters to trade-off complexity and data rates. Using a 30 Gbd QPSK signals, we study a joint optimization of the FEC overhead, PR iterations and PR pilots overhead. Our results shows that by this optimization, the PR iteration number can be reduced by 66% with respect to conventional hard-decision FEC (HD-FEC) with 8% OH.

Overhead allocation between Phase retrieval pilots and FEC

Fig. 1 shows the overhead allocation problem between PR and FEC. For a given overall OH, the red triangle move to left indicates more knowledge of the phase and weak error correction capability. Otherwise, little knowledge of the phase and stronger error correction capability will be provided.

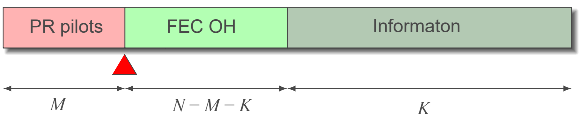

Fig. 1: PR pilots vs. FEC overhead.

Note the PR pilots are symbol-wise and binary FEC redundancy are bit-wise, here M indicate the equivalent pilot symbols in bits, which depends on the selection of modulation formats. The overall overhead can be calculated as $\text{OH} = 1/R - 1$, where R is the overall rate as

$$R = \frac{1}{1+\text{OH}_{\text{FEC}}} \cdot \frac{1}{1+\text{OH}_{\text{PR}}} = \frac{K}{N-M} \cdot \frac{N-M}{N} = \frac{K}{N},$$

where $M = \frac{\text{OH}_{\text{PR}}}{1+\text{OH}_{\text{PR}}} R_s \log_2 \mathcal{M}$, R_s is the symbol-rate and $\mathcal{M}$ is the cardinality size of constellation.

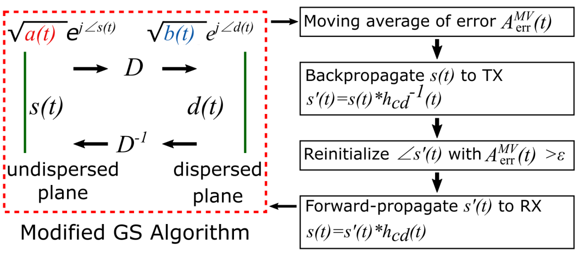

Fig. 2: Schematic diagram of PR algorithm with selective phase reset.

In this paper, we use the modified GS algorithm with selective phase resets to achieve PR with only one dispersive projection[6]. The schematic diagram is shown in Fig. 2. Given the knowledge of intensity $a(t)$ without dispersive element and intensity $b(t)$ with dispersive element, the algorithm iteratively refines the estimate of the complex-value $s(t)$ and its dispersived counterpart $d(t)$, whose relationship $h_{cd}(t)$ is linked by the well-known transfer function of chromatic dispersion. The algorithm is applied in a block-wise manner. The process of each iteration is clearly described in our previous work[6]. Symbol-wise GS error is defined as $A_{\text{err}}(t) = |a(t) - |s(t)|^2|$, where $a(t)$ is the intensity at the undispersed plane. After three iterations of GS algorithm, moving average of 10 symbols of $A_{\text{err}}(t)$ is calculated and phase reset process is applied to reinitialize $\angle x'(t)$ where $A_{\text{err}}^{MV}(t) > \varepsilon$. The parameter ε is an acceptable GS error level and set to -26 dB in our experiment. The usage of $A_{\text{err}}^{MV}(t)$ helps to remove error spikes that disturb convergence, thus achieving fast convergence and avoiding local minima.

We adopt one of the most popular families of HD-FEC codes, staircase codes (SCCs)[7] as FEC scheme. The component code Bose-Chaudhuri-Hocquenghem (BCH) is defined with parameters of (n, k, t), where n is the codeword length, k is the information length and t is the error-correcting capability. The resulted SCC code rate is $R_{\text{SCC}} = 2k/n - 1$.

Experimental Setup

Fig. 3 shows the experimental setup for detecting a single-polarization Nyquist-shaped 30 Gbaud QPSK signal by PR receiver. A 55-km single-mode fiber (SMF) span was applied as the dispersive element. The dispersion differences of two branches at the PR receiver introduce symbol mixing and intensity variations, which constitute two alternative projections. An external cavity laser with a linewidth of 100 kHz at 1550.06 nm wavelength was modulated by an in-phase and quadrature Mach-Zehnder modulator. The spectral roll-off factor of QPSK signal was set to 0.1. Two erbium-doped fiber amplifiers (EDFAs) were used before and after the 55-km SMF to compensate the link loss. Within the PR receiver, an optical filter was applied to filter out the out-of-band noise. A digital sampling oscilloscope at 80 GSamples/s captured dual-channel electrical signals, and afterwards 4 million samples were sent to post processing.

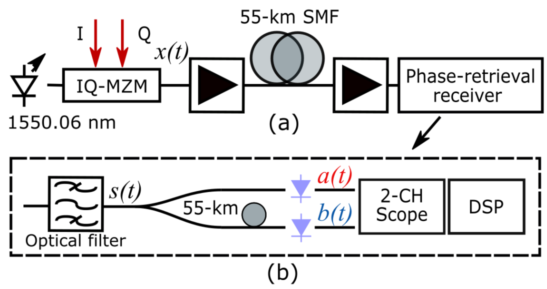

Fig. 3: Experimental setup for detecting 30 Gbaud QPSK signal after 55-km transmission using PR.

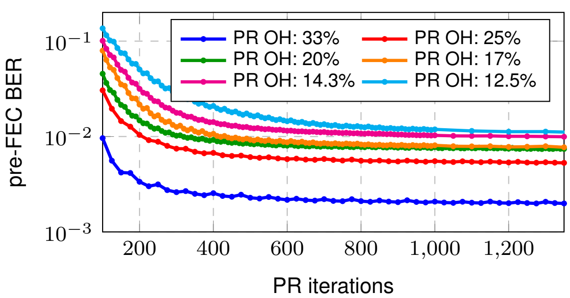

Fig. 4: Pre-FEC BER vs. iteration number of PR.

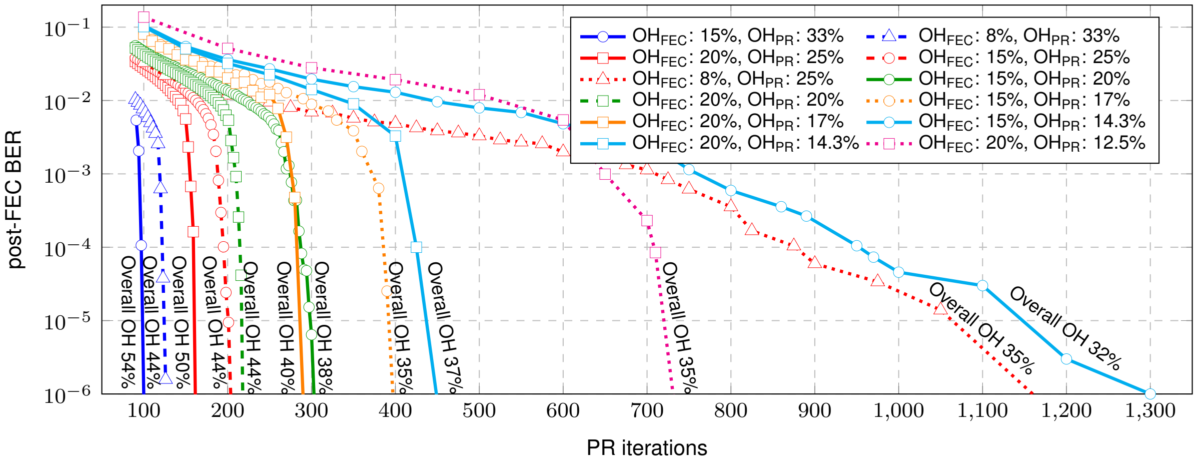

Fig. 5: Post-FEC BER vs. PR Iterations. The overall OHs are calculated by OH_{FEC} and OH_{PR}.

Experimental results

Fig. 4 shows the measured pre-FEC BER vs. the number of iteration for phase retrieval with different PR OH. As can be seen, for higher PR pilots case, faster convergence can be realized and a lower convergent BER is obtained, but it also reduces OH for FEC when the same net data rate is required. Therefore, it is clear that the overhead allocation between PR and FEC become a key parameter to optimize the performance for a fixed net data rate.

We do a joint optimization in which we varied the PR pilots overhead between 12.5% and 33% as well as the SCC overhead between 8% and 20%. We consider three SCC rates: $R_{\mathrm{SCC}} = \{0.925, 0.867, 0.833\}$, which are corresponding to OH_{FEC} of $\{8.15\%, 15.31, \%20\%\}$, respectively. These three SCC codes are generated by (shortened) BCH codes with parameters of $(504, 485, 2)$, $(256, 239, 2)$ and $(228, 209, 2)$. The decoding window size is 9, and the maximum number of iterations is 7.

Fig. 5 shows results of BER vs. PR iteration number with six PR pilots (different colors) and three SCCs (different markers). When comparing the results for higher PR pilots OH, we observe that SCCs lead to a steeper waterfall performance. This comes from the fact that the steepness of the pre-FEC BER curves (see Fig. 4) are in the waterfall region of SCC, which is determined by error correction capability of FEC. For the signal lower PR pilots OH, in order to achieve error free transmission, higher FEC OH and more PR iterations are required.

In order to have a better understanding the observed results in Fig. 5, the joint optimization of overall OH and PR iterations for post-FEC BER$\leq$1e-6 is shown in Fig. 6. It can be observed that the optimum PR iteration number tends to

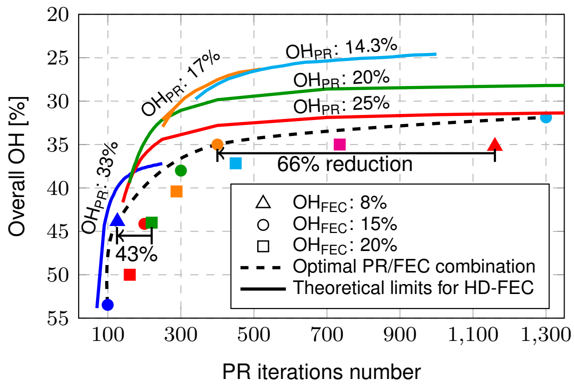

Fig. 6: Overall OH vs. PR Iterations for post-FEC BER$\leq$1e-6.

decrease when having larger overall overhead. For the overall OH of 35% and 44%, the iteration number of PR is reduced by 66% and 43%, respectively. The optimal PR/FEC overhead allocation is found as the dashed curve and the theoretical limits for HD-FEC are also highlighted as solid curves based on the ideal HD-FEC assumption, which can be achieved by more powerful FEC with longer codeword and larger decoding capability. It is also interesting to note that in systems requiring complexity, bit rate adaptation, joint adaptation of pilots overhead and FEC overhead should be performed to achieve best performance for each bit rate.

Conclusions

We have experimentally shown that the the overhead trade-off between phase retrieval pilots and staircase codes can improve the performance of data rate and the required iteration for PR. 66% iteration number can be reduced in an optical transmission system if the overhead allocation is re-optimized.

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