# Weak Carrier Assisted Phase Retrieval Receiver

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**Abstract:** We propose a weak carrier-assisted phase-retrieval receiver to obtain initial phase for modified Gerchberg-Saxton algorithm with fast convergence to realize hardware-efficient, computationally-efficient, and pilot-symbol-free optical field recovery, and compare it with other phase retrieval schemes.

## 1. Introduction

To reconstruct the optical field, several self-coherent direct detection schemes have been proposed including Stokes vector receiver (SVR) [1] and Kramers-Kronig receiver (KKR) [2]. However, the SVR needs at least three single-ended photodiodes (PDs) and an optical hybrid, and the KKR requires a strong carrier to satisfy minimum phase condition. Recently, phase-retrieval (PR) receivers based on the modified Gerchberg-Saxton (MGS) algorithm [3] have shown that full field recovery can be demonstrated employing 2 PDs and a dispersive element by searching for optimum phases that satisfy the relation between the projections [4-6]. In [4], it requires phase rest to escape from local minima and 20% pilot symbols to eliminate the constant phase ambiguity across the thousands of iterations process. Although the performance of PR receiver could be enhanced by employing parallel alternative projections [7] or space-time diversity [8], the cost of hardware is close to that of a single-polarization coherent receiver. In addition, dozens of iterations and 20% pilot symbols are still necessary in space-time diversity phase retrieval (STD-PR) receiver. The schemes using pilot symbols including PR with phase reset (PR-PR) and STD-PR need digital back propagation (DBP) and phase update at the transmitter, leading to high redundancy and computational complexity. We attribute the demand for pilots and large number of iterations (NOI) to the lack of a good initial point, which is very important in convex optimization theory.

In this paper, we propose a weak carrier-assisted phase-retrieval receiver (WCA-PR) to significantly to improve the comprehensive performance of PR. The key idea is to use a weak carrier to obtain an initial phase to substitute the random phase in the conventional PR-PR and STD-PR. The new scheme shows: 1) extremely fast convergence speed (i.e. less than 10 iterations) and dramatic reduction in the NOI for field recovery; 2) low computational complexity (no DBP to transmitter) compared with PR-PR and STD-PR; 3) simple hard-ware structure (2 PDs and a dispersive element); and 4) low redundancy (no pilot symbol). To compare with the previous work [4,8], we carry out numerical simulations for single-carrier 30Gbaud QPSK signal transmission over 55km SSMF. In the case of 16dB OSNR, to reach the bit-error-rate (BER) threshold of 7% HD-FEC, 1 and 5 iterations are needed under carrier-to-signal power ratio (CSPR) of -1 dB and 0dB at BTB scenario and after 55km SSMF, respectively.

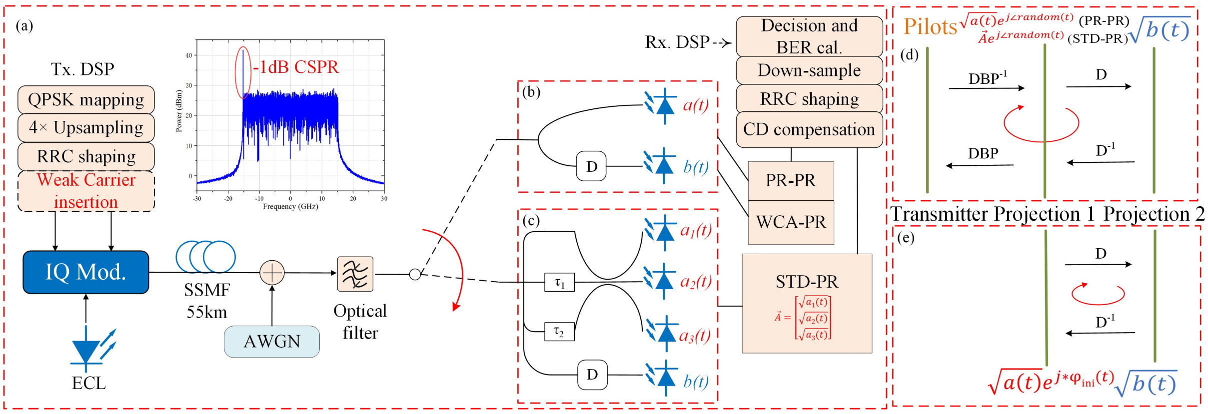


Fig. 1. (a) Simulation setup and DSP stack; (b) Structure of PR-PR and WCA-PR; (c) Structure of STD-PR. (d) Modified GS algorithm for PR-PR and STD-PR; (e) Modified GS algorithm for WCA-PR.

## 2. Principle

The optical field of undispersed plane ((projection 1 in Fig.1(e))) could be denoted as $W_C e^{-j\pi Bt} + S(t)$ , where $W_C$, $S(t)$, and $B$ are the weak carrier, optical signal and signal bandwidth, respectively. The weak carrier is inserted at the edge of the signal spectrum shown in Fig.1(a). Its true phase is $\angle\{W_C e^{-j\pi Bt} + S(t)\}$, where $\angle$ is the angle function. After PD, the photocurrent detected on the undispersed plane could be written as:

$$a(t) = \left|W_C e^{-j\pi Bt} + S(t)\right|^2 = \left|W_C\right|^2 + W_C^{*} e^{j\pi Bt} S(t) + W_C e^{-j\pi Bt} S(t)^{*} + \left|S(t)\right|^2. \tag{1}$$

Assisted with the weak carrier, we can obtain an initial phase distorted by signal-to-signal beat noise, given as:

$$\varphi_{ini}(t) = \angle\{R[a(t)/W_C^{*}]e^{-j\pi Bt}\} = \angle\{W_C e^{-j\pi Bt} + S(t) + R[|S(t)|^2/W_C^{*}]e^{-j\pi Bt}\}, \tag{2}$$

where R[.] denotes a sideband filter aimed to remove conjugation term $W_C e^{-j\pi Bt} S(t)^{*}$. Fig.1(e) illustrates the iteration process of proposed WCA-PR. We take the $\varphi_{ini}(t)$ as the initial phase and then conduct MGS algorithm just between 2 projection planes without DBP to transmitter. After several iterations, the optical field could be retrieved.

## 3. Simulation setup and results

To validate the feasibility of proposed WCA-PR and compare it with PR-PR and STD-PR fairly, we conduct simulations, with the same configuration as [8]. Specifically, the transmitted signal and fiber channel are single-carrier 30G-Baud QPSK signal with 0.01 roll-off factor and 55km SSMF, respectively. The symbol length is $2^{10}$ for PR-PR/STD-PR and $2^{12}$ for WCA-PR. The simulation setup and DSP stack are shown in Fig.1(a). To simplify the performance comparison, the phase reset parameter is 200 and the acceptable error level is 0.002 for conventional PR-PR, which is a reasonable setting according to [4]. The number of total iterations is set at 2000 for to ensure the algorithm convergence, and 20% periodically inserted pilot symbols are used for PR-PR and STD-PR. First, we show the extremely fast convergence speed of WCA-PR at BTB scenario. Fig.2(a) shows the mean absolute phase error |Δθ| versus the NOI with 3 PR schemes under 16dB OSNR. The process of the first ten iterations is shown in the inset. For PR-PR/STD-PR and WCA-PR, the initial mean of |Δθ| are 1.57 and 1.0621, respectively. After 1 iteration and 5 iterations, the mean of |Δθ| for WCA-PR is 0.1971 and 0.1774, respectively. The absolute phase error of symbol sequence after 0 iteration, 1 iteration and 5 iterations and constellations are depicted in Fig.2(b). It shows only one iteration is needed to reach the BER threshold of 7% HD-FEC and takes 5 iterations to realize full phase retrieval. The residual absolute phase error results from the Gaussian noise. The steady bit-error-rate (BER) performance is confirmed through 2000 simulations. Histograms of the 2000 simulated BERs under 14dB OSNR are as shown in the histograms of Fig.2(c). It can be observed that the frequency distribution of WCA-PR is more concentrated than PR-PR, indicting more stable BER performance. We attribute the stability to the calculated initial phase, eliminating the instability caused by the random phase in PR-PR, which enhances the practicality of PR receiver for field deployment.

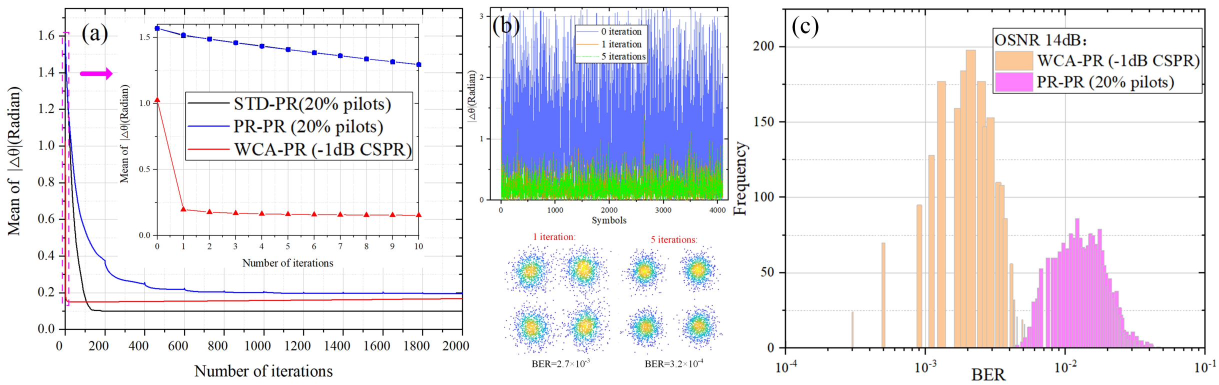


Fig. 2(a) Mean absolute phase error versus the NOI; (b) Absolute phase error of symbol sequence and constellations after 1 iteration and 5 iterations; (c) Histogram of 2000 simulated BERs under 14dB OSNR for PR-PR and WCA-PR.

Then, we investigate the effect of the dispersive element on the performance of WCA-PR and PR-PR. Fig. 3(a) depicts the converged BER with respect to the CD value under 16 dB OSNR. It shows that 374 ps/nm dispersion is sufficient for WCA-PR to realize phase retrieval while the BER performance of PR-PR improves slightly with the increase of applied dispersion. The characteristic enables more practical PR receiver. The BERs versus CSPR under different OSNRs and the NOI versus CSPR under 18dB OSNR after 55km transmission are shown in Fig.3(b). In the case of fixed OSNR, with the increase of CSPR, the NOI could be further reduced, but the effective

OSNR will decrease, resulting in the degradation in BER performance. The BERs versus the NOI under different OSNRs are displayed in Fig.3(c). It shows that the required NOI decreases with OSNR increasing.

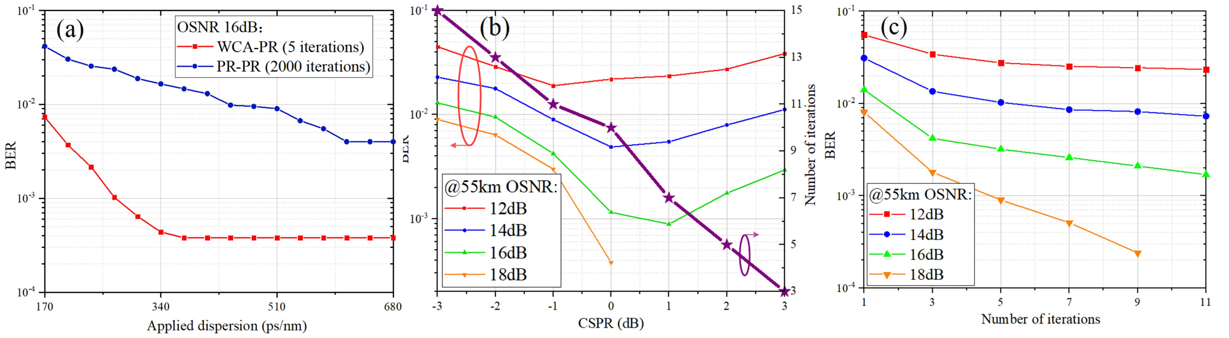


Fig. 3(a) BERs versus the applied dispersion in the PR receiver; (b) BERs versus CSPR under different OSNRs and the number of iterations versus CSPR under 18dB OSNR;(c) BERs versus the number of iterations under different OSNRs.

## 4. Comparison of phase retrieval schemes

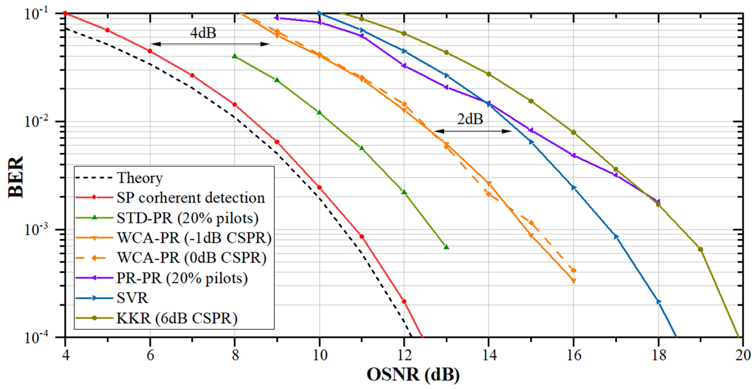


Fig. 4. OSNR sensitivity comparison at BTB scenario.

| | PR-PR | STD-PR | WCA-PR |
|---|---|---|---|
| **Hardware complexity** | Low | High | Low |
| **Number of iterations** | ~2000 | ~50 | <10 |
| **Pilot symbols** | 20% | 20% | 0% |
| **Applied dispersion** | Large | Small | Small |
| **OSNR penalty** | >6dB | ~2dB | ~4dB |

Table. 1. Comparison of PR schemes

We analyze the OSNR sensitivity of different PR schemes, including single-polarization (SP) coherent detection, SVR, KKR, PR-PR, STD-PR, and proposed WCA-PR. The applied dispersion for 3 PR receivers is set as 650 ps/nm. The results are shown in Fig.4. The OSNR penalty of WCA-PR to the ideal coherent detection is only 4 dB using a hardware-efficient receiver, where there is about 3 dB intrinsic OSNR penalty results from the weak carrier. Another 1dB results from the convergence error of MGS algorithm due to insufficient amount of dispersion. Under the same 0dB CSPR, it outperforms SVR by 2dB in a hardware-efficient way and there is ~3dB improvement over KKR with 6dB CSPR. Note that although the OSNR sensitivity of WCA-PR is 2dB lower than that of STD-PR, the net rate of WCA-PR is 20% higher due to the 20% pilot symbols. As references, we list the key parameters in Table. 1 for the 3 PR schemes discussed in this section.

## 5. Conclusion

We propose a weak carrier-assisted phase-retrieval receiver to significantly to enhance the comprehensive performance of PR. The convergence speed, computational complexity, stability and practicality of PR are considerably improved. The simulated OSNR penalty to the single-polarization coherent detection is 4 dB without using narrow linewidth local oscillator.

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