Research on Carrier Recovery Algorithm in Coherent Optical Communication System

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Abstract. In coherent optical communication system, the random deviation of optical phase which is caused by the spontaneous emission of laser leads to phase noise, resulting in a random rotation of signal constellation. In order to ensure the reliability of the communication system, carrier phase estimation and recovery are required at the receiver. In this paper, we investigate two traditional carrier phase recovery (CPR) algorithms, including Viterbi&Viterbi phase estimation (VVPE) and blind phase search (BPS) algorithm. On this basis, we also discuss seven improved algorithms. Then we compare and analyze the hardware complexities of eight different CPR algorithms. In addition, the cause of equalization enhanced phase noise (EEPN) and its impact on the carrier phase recovery algorithm are also discussed.

1. Introduction

In recent years, with the continuous emergence of high-tech such as 5G and cloud computing, the demand for a large amount of data storage and sharing has been significantly increased. With its enormous bandwidth advantage, optical fiber has become an important medium for information transmission. Optical fiber communication systems can be divided into intensity modulation/direct detection(IM/DD) systems and coherent optical communication systems. Facing with the higher bandwidth requirements, traditional IM/DD systems cannot satisfy the demand for transmitting large-capacity data in future. Improving the capacity of optical fiber communication systems has become an urgent issue. Based on high-speed optical devices and digital signal processing(DSP) technology, coherent optical communication system can effectively overcome the problems of IM/DD system.

However, there are also some problems in coherent optical communication systems, such as the effects of carrier phase noise. In coherent optical communication system, especially a phase shift keyed(PSK) coherent optical communication system, because data information is carried through phase changes of optical carrier, phase noise is a transmission loss which cannot be ignored. The generation of phase noise is mainly due to the random deviation of the optical phase, which is caused by the spontaneous radiation of the laser in the coherent receiver. Phase noise would result in random rotation of signal constellation, leading to a larger bit error ratio (BER) and reducing the reliability of the communication system. Therefore, it is necessary to compensate carrier phase noise at the receiving end, rotate the constellation diagram to the correct position, and recover the transmitted signal accurately.

In addition, it is found that the phase noise of local oscillation (LO) laser at the receiver is greatly enhanced by the interaction of the electronic dispersion compensation module. Due to the existence of dispersion, the transmitted optical pulse is broadened, which will make the data information cannot be recover correctly in the receiving system, deteriorating the performance of the coherent optical communication system significantly.
With the rapid development of electronic dispersion compensation technology in optical communication systems, it is also meaningful to study the influence of EEPN on different CPR algorithms.

In this paper, we first introduce two traditional CPR algorithms, including VVPE and BPS. On this basis, we also discuss seven improved algorithms, and analyze the hardware complexities of eight CPR algorithms. Moreover, the causes of EEPN and its impact on the CPR algorithms are also investigated.

2. Traditional CPR Algorithms

2.1. VVPE

VVPE scheme is a pre-feedback CPR algorithm[1]. It removes the phase modulation information of the optical signal and restores the original data information by calculating the Mth power of the received optical signal, which is widely used in the PSK modulation format system.

Figure 1 shows the schematic diagram of VVPE algorithm. It can be seen that the received optical signal is divided into two branches. In branch 1, arg (*) function is utilized to extract phase information. In branch 2, the signal first undergoes quadratic processing. The phase information can be extracted by utilizing the same function with branch 1 and then divided by 4. Through subtracting branch 1 and branch 2, the phase information without noise interference can be obtained.

![Figure 1. The schematic diagram of VVPE.](image)

2.2. BPS

The schematic diagram of BPS algorithm [2] is depicted in Figure 2. We can see that this algorithm is divided into different decision circuits for phase estimation initially, and then it multiplies the received optical signal by the test phase and performs the operation of subtraction. We can see that this algorithm is divided into different decision circuits for phase estimation initially, and then it multiplies the received optical signal by the test phase and performs the operation of subtraction. Finally, it calculates the minimum modulus value to estimate the phase noise value. This algorithm is suitable for any M-QAM modulation format.

![Figure 2. The schematic diagram of BPS.](image)
3. Improved CPR Algorithms

VVPE is based on the feature that QPSK has the same phase angle and is not suitable for high-order modulation formats. Although the BPS algorithm can effectively compensate the phase noise of M-QAM signal, the computational complexity is considerably high. In order to optimize the CPR algorithm for high-order modulation, many improved algorithms have been proposed. We analyze and summary these algorithms in the following paragraphs.

3.1. Improved CPR Algorithms based on VVPE

3.1.1. CT algorithm. Constellation Transform (CT)[3] is an algorithm that allows the VVPE-based estimation method to directly estimate the phase of the signal by coordinate operation, which greatly enhances the performance of the CPR algorithm. Its coordinate transformation formula is:

\[ Y = [X_r - \text{sign}(X_r - 2\text{sign}(X_i))] + j[X_i - \text{sign}(X_i - 2\text{sign}(X_i))] \]  

(1)

After the coordinate transformation, the 16QAM constellation becomes QPSK[4] format, so the VVPE-based algorithm can be used for detailed phase estimation.

The further promoted CT method is Crossed Constellation Transform (CCT). CCT extends the applicable modulation format from 16QAM to M-QAM. The transformation formula is:

\[ Y = [X_r - A_i \text{sign}(X_r - B_i \text{sign}(X_i))] + j[X_i - A_o \text{sign}(X_i - B_o \text{sign}(X_i))] \]

(2)

The CCT diagram is shown in Figure 3:

3.1.2. MP and 8th power algorithm. The Modified Partitioning(MP) algorithm improves the algorithm by modifying the QPSK partition. The algorithm firstly classifies it by 16-QAM signal partitioning method, and then performs 4th power operation uniformly and rotates \( \pm \theta \) on the intermediate ring[5]. After that, it uses VVPE algorithm to complete carrier phase estimation. The schematic diagram is shown in Figure 4.

Data Block → Partition → \( S^4 \) → Rotating Intermediate ring \( \pm 4\theta_{\text{rot}} \) → VVPE

3.1. The diagram of MP.
The 8th power algorithm [6] is to approximate the intermediate ring C2 as a signal with a phase distance of π/8, and perform π/8 rotation processing on the inner and outer rings C1 and C3. Then it utilizes 8th power operation and VVPE to obtain the carrier phase estimation value. The schematic diagram is shown in Figure 5.

$$e^{-j\theta_{est}}$$

Figure 5. The diagram of eighth-order algorithm.

3.1.3. P123 partition algorithm. In order to improve the performance and reduce the computational complexity of the phase estimation algorithm, a combination of multiple cascaded algorithms is widely used. The most representative multi-stage phase estimation algorithm is QPSK partition + CCT + Maximum Likelihood(ML)[7], so that the VVPE-based estimation method can be applied to the M-QAM modulation format. The algorithm flow is shown in Figure 6. In the multi-stage phase estimation algorithm, the phase tracking capability of the first stage has an important effect on the laser linewidth that the overall algorithm can tolerate. On this basis, ref [7] proposes a multi-level phase estimation algorithm for 32QAM. In this method, the first stage uses a quasi QPSK Partitioning method for phase estimation to enhance the algorithm's ability to cope with phase changes.

$$y = \sum_{j=1}^{N} S[j] \cdot \overline{S[j]}$$

$$\tan^{-1}\left(\frac{\text{Im}(y)}{\text{Re}(y)}\right)$$

Figure 6. The schematic diagram of P123 partition algorithm.

3.2. Improved CPR Algorithms based on BPS

Although the BPS scheme can accurately estimate the phase noise in the M-QAM signal, the implementation process needs to rotate all possible phases of the signal, and then performs operations such as squaring, comparison, and decision, which puts high requirements on hardware performance and increases system cost. In order to simplify the complexity of the system and meet the requirements of high-order modulation systems, researchers have proposed many improved algorithms based on this.

3.2.1. BPS-ML algorithm. In order to reduce the computational complexity of the BPS algorithm, an improved method of cascading BPS algorithm and ML estimation algorithm is proposed [8].

In the first phase, the rough BPS algorithm is used to find the location of the optimal phase angle. Then, the phase information after the rough phase estimation is subjected to more accurate phase estimation by the ML estimation algorithm of the second stage. This method greatly reduces the number of search phases and computational complexity and improves the accuracy of phase estimation.
3.2.2. **BPS-QA algorithm.** BPS-QA is a quadratic approximation (QA) algorithm based on BPS [9]. Figure 7 shows the schematic diagram. After using the first-order rough estimation of BPS, the algorithm performs the local optimal phase estimation on the test phase and the minimum Euclidean distance in the second-order algorithm.

\[
\begin{align*}
\text{If:} & \quad \phi_{i-1} < \phi < \phi_{i+1} \\
\text{Minimize:} & \quad |\phi_{QA} - \phi| < \varepsilon \\
\text{Then:} & \quad \phi_{k+1} = \phi_{QA}
\end{align*}
\]

![Figure 7. The schematic diagram of BPS-QA algorithm.](image)

Firstly, it performs a first-order estimation, selects the test phase with the smallest sum of distances and the two test phases in the vicinity. Secondly, it fits the three test phases and distances into the following formula:

\[
\begin{align*}
& a + b\phi_{b1} + c\phi_{b1}^2 = e_{b1} = f(\phi_{b1}) \\
& a + b\phi_{b2} + c\phi_{b2}^2 = e_{b2} = f(\phi_{b2}) \\
& a + b\phi_{b3} + c\phi_{b3}^2 = e_{b3} = f(\phi_{b3})
\end{align*}
\]

Get the optimal test phase and minimum distance sum, and then iterate to the kth time to satisfy:

\[
|\bar{\phi}_k - \bar{\phi}_{k-1}| < \varepsilon
\]

\(\bar{\phi}_k\) is just the final estimated phase.

3.2.3. **Four-dimensional(4-D) BPS CPR scheme.** For one thing, the existing CPR scheme of set-partitioning quadrature amplitude modulation (SP-QAM) formats is independently implemented between two polarization signals. For another, the laser linewidth tolerance of SP-QAM is restricted the same as conventional QAM signals. Therefore, Jianing Lu et al. proposed a new four-dimensional CPR scheme for SP-QAM format in 2018 [10]. After the phase offset estimation and pre-compensation between two polarizations, they implement BPS algorithm in the 4-D space. At the same time, the traditional decision circuit is replaced by the 4-D detection of SP-QAM, and the four-dimensional distance is calculated as a cost function for identifying the required test phase angle. The schematic diagram is shown in Figure 8.
Figure 8. The schematic diagram of 4D BPS scheme.

Through numerical simulations under the coherent transmission conditions of 28 Gbaud SP-128-QAM, SP-512-QAM and SP-2048-QAM, it can be obtained that the proposed 4-D BPS has better CPR performance and robustness under the condition of the same complexity as the traditional BPS.

4. Comparison of the hardware complexity of multiple algorithms

The hardware complexity of DSP algorithms is closely related to the difficulty and cost of engineering applications. Furthermore, it also determines whether the algorithm can realize real-time processing in high-rate transmission systems. Here, the hardware complexity of eight algorithms with better performance is compared[11].

Table 1. Hardware complexity of carrier phase estimation algorithms.

| Algorithm          | Multiplier  | Adder         | Comparator | Judgment |
|--------------------|-------------|---------------|------------|----------|
| P123               | 18N+3       | 12N           | 1          | N        |
| P3+CT              | 7N1B+1/2N1+10N2+4 | 4N1+10N2   | N1+2      | N2       |
| P3+MP              | 7N1B+1/2N1+12N2+2 | 4N1+N2     | N1+N2+2   | N2       |
| BPS                | 6NB+4N      | 6NB-B+2N2+2  | B          | NB+N     |
| BPS+ML             | 6N1B+8N2+1  | 6N1B-B+6N2   | B          | N1B+N2   |
| BPS+CT             | 6N1B+4N1+10N2+2 | 6N1B-B+2N1+10N2+2 | B+1       | N1B+N2   |
| BPS+MP             | 6N1B+4N1+14N2 | 6N1B-B+2N1+8N2+2 | B+N2      | N1B+N2   |
| BPS+QA             | 6N1B+16N2+56 | 6N1B-B+14N2+37 | B+6       | N1B+3N2  |

Among these methods, P3 represents the phase estimation using the partition algorithm of the outer circle signal data. Because its data utilization rate is only 25%, the performance is really poor and generally only used as the first-order rough estimation.

Taking the 16-QAM back-to-back transmission system as an example, the hardware complexity of each algorithm is more intuitively compared, and various carrier phase estimation algorithms take the best test phase and the optimal code length. After calculation, the hardware complexity of each carrier phase estimation algorithm is shown in Table 2.
Table 2. Hardware complexity of carrier phase estimation algorithms in 16-QAM system.

| Algorithm | Multiplier | Adder | Comparator | Judgment |
|-----------|------------|-------|------------|----------|
| P123      | 723        | 480   | 101        | 40       |
| P3+CT     | 679        | 500   | 52         | 30       |
| P3+MP     | 737        | 410   | 82         | 30       |
| BPS       | 3920       | 3850  | 32         | 660      |
| BPS+ML    | 3920       | 3850  | 32         | 660      |
| BPS+CT    | 2222       | 2152  | 11         | 330      |
| BPS+MP    | 2340       | 2092  | 70         | 330      |
| BPS+QA    | 1260       | 1198  | 11         | 207      |

It can be seen that the carrier phase estimation algorithm based on VVPE partitioning method has relatively low hardware complexity, while the classical BPS algorithm uses more multipliers, adders and judgments. So the hardware complexity of the two-stage association estimation algorithm based on BPS is also relatively high.

5. EEPN and its impact on CPR

In a coherent optical communication system with electronic dispersion compensation (EDC), it is observed that the received constellation is still affected by enhanced noise even after DSP [12], which is commonly referred to as equalization enhanced phase noise (EEPN). Recent frequency domain analysis shows that EEPN is generated due to the nonlinear mixing between the sidebands of the scattered signal and the noise sideband of the LO [13]. Eliminating EEPN or limiting it below a certain cutoff frequency will significantly reduce the transmission cost.

5.1. Formula Analysis of EEPN

The time domain response \( r'(t) \) of the received signal affected by EEPN in the EDC coherent optical system is [14]:

\[
r'(t) = \sum_{n=-\infty}^{\infty} e^{\frac{k f_s}{\pi}} \cdot e^{-j \beta f_s^2} \cdot e^{j \beta (\frac{f_s}{\pi})} \cdot e^{j \frac{\pi}{2} \beta f_s^2} \cdot df_s
\]

The estimation of the impact of EEPN on LO system performance with white noise can be described by optical signal-to-noise ratio (OSNR):

\[
\text{Penalty} = -10 \cdot \log_{10}(1 - [\text{OSNR}_{\text{ref.inband}} \cdot \pi^2 \cdot |\beta| \cdot L \cdot \text{Baudrate} \cdot \text{LW}])
\]

For a general modulation format Lorentzian linewidth laser, the cutoff frequency (mitigation bandwidth) required to limit the EEPN cost (dB) is:

\[
f_{\text{cutoff}} = LW \cdot \tan(\pi \cdot \frac{\text{Penalty}}{2 \cdot \frac{10}{\text{OSNR}_{\text{ref.inband}}}})
\]

In 2016, Aditya Kakkar et al. first gave experimental verification of the new analytical expressions necessary for the design of coherent optical systems affected by EEPN [15]. These expressions support simple and accurate EEPN analysis and are applicable to any system specification.

5.2. The suppression of EEPN

5.2.1. VVPE algorithm under EEPN. Ref [16] performs simulation analysis under different conditions, including the electronic dispersion compensation completely used, and the optical and electric domain...
dispersion compensation utilized simultaneously. The relationship between the BER and the OSNR when using the VVPE scheme is shown in Figure 9 [16].

![Figure 9](image)

Figure 9. The performances of three dispersion compensated coherent optical communication systems.

It can be seen that in the 100% electronic domain dispersion compensation, due to the influence of EEPN, even if the OSNR is increased to 20 dB, the BER of the signal is not significantly reduced. In the hybrid dispersion compensation mode, the EEPN introduced by compensating for residual dispersion has a limited effect on system performance, and its total BER is much lower than that at 100% EDC compensation. In the hybrid dispersion compensation mode, the BER is the lowest when there is ideal case of no EEPN.

Therefore, hybrid dispersion compensation is not only suitable for high-speed optical coherent communication, but also has obvious advantages of resisting EEPN and reducing system nonlinearity.

5.2.2. Low bandwidth digital coherence enhancement (DCE) method. In 2015, Aditya Kakkar et al. proposed a simple low-bandwidth DCE method that reduces EEPN in coherent optical systems. This method is suitable for real-time implementation and requires hardware bandwidth far below the signal baud rate. Its implementation method is shown in Figure 10[17].

![Figure 10](image)

Figure 10. Causal low-speed DCE architecture.

Relevant researchers have performed simulation analysis of long-distance transmission links in QPSK and 16-QAM formats, evaluating the interpolation techniques, electrical signal-to-noise ratio, and other parameters required for the DCE front-end. It is demonstrated that a low-speed DCE front end and a simple digital linear interpolator can achieve a small (<1 dB) implementation penalty even in extreme cases, which is sufficient to mitigate the damage of EEPN.
6. Summary
In this paper, we mainly discuss two traditional CPR algorithms, including VVPE and BPS. VVPE is the earliest CPR algorithm in DSP, which is mainly used in m-PSK modulation format and very sensitive to phase noise. Therefore, simply improving the OSNR cannot enhance the system performance considerably. BPS can be applied to various modulation formats and its estimation accuracy is relatively better. However, its computational complexity is extremely high, which is difficult to implement in practice. Therefore, a number of improved algorithms have been proposed based on them. The hardware complexities of eight CPR algorithms are analyzed. Tests and experimentation have verified that the performances of the algorithms have been improved in different level.

Moreover, we also discuss EEPN. The nonlinear mixing between the sidebands of the scattered signal and the noise sidebands of the LO produces EEPN, which leads to an increase in the phase noise variance of the signal and degrades the performance of the CPR module. We summarize two methods to reduce the impact of EEPN. One is hybrid dispersion compensation, and the other is low bandwidth DCE.

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