Optical Comparator for 4-Bit and 6-Bit QPSK-Modulated Signals by Using Optical Delayed Interferometer

Volume 10, Number 2, April 2018

Yohei AIKAWA

DOI: 10.1109/JPHOT.2018.2822316
1943-0655 © 2018 IEEE
Abstract: In this paper, a novel optical comparison operation for phase-shift keying (PSK) modulated signal has been proposed by using optical delayed interferometer to realize an advanced functional component for future optical network. The feasibility of the optical comparators designed for 4-bit and 6-bit codewords was experimentally demonstrated. It has been shown that the constellations obtained from each comparator are located in conformity with a Hamming distance between a comparator code and a given codeword, which is comprised of a successive two and three QPSK-modulated RZ symbols at 10.72 Gbaud/s. It was concluded that the proposed scheme offers a comparison operation for 4-bit and 6-bit codewords at 10 Gbaud/s.

Index Terms: Optical comparator, optical signal processing, optical delayed interferometer.

1. Introduction

To overcome the bottleneck of electrical processing rate in optical communication system, the demand for optical signal processing has attracted a growing interest due to its potential for low-power operation. Recently, various investigations have been conducted on the advanced technologies of optical signal processing. Specifically, the technologies contain optical label recognition [1], [2], optical bit pattern generator [3], [4], optical half- and full-adder [5]–[7], optical encryption [8], [9], optical correlator [10], [11], and optical comparator [12]–[17].

In particular, optical comparator is of considerable concern because the technology is widely applicable in a technical field of communication system. The technologies of optical comparator can be divided into two categories in terms of control method: to control the comparator by i) optical signal and ii) electrical signal. Specifically, optically-controlled schemes involve semiconductor optical amplifiers [12], [13], nonlinear fiber ring resonator [14], Fabry-Perot laser diode [15], and micro ring resonator [16]. In contrast, electrically-controlled scheme contains an electro-optical ring resonator [17].

On the other hand, both types of comparator are not well suited for advanced optical network, because both schemes relate to only On-Off keying (OOK) modulation. The optical comparator for Phase-Shift keying (PSK) modulation is desirable due to its superior sensitivity for high-speed and long-haul transmission. However, there have been no reports of such kind of optical comparators,
as far as we know. In this paper, the author proposed a novel optical comparator applied to PSK modulation by using optical delayed interferometer. The feasibility of the comparison operation was experimentally investigated for 4-bit and 6-bit Quadrature PSK (QPSK) modulated signals at 10 Gbaud/s.

2. Operating Principles

The basic idea of the proposed scheme is to provide constellations, whose coordinates in a complex plane are located in conformity with a positional relationship of given codewords in a coding space. When some codewords consisting of \( n \)-th binary sequence are given, the codewords are located at each position in a \( n \)-dimensional coding space. In the coding space, a difference between two codewords is quantitatively evaluated by Hamming distance, and it is derived as

\[
d_H(x, y) = \sum_{k=0}^{n-1} | x_k - y_k |, \tag{1}
\]

where \( x = x_0, x_1, \ldots, x_{n-1} \) and \( y = y_0, y_1, \ldots, y_{n-1} \) are \( n \)-th binary sequence of the codewords, and the Hamming distance provides the number of coefficients in which they differ. Therefore, the purpose of our scheme is to match the Hamming distance of given codewords and the Euclid distance of their constellations.

Fig. 1 provides a conceptual image of the proposed scheme. In this case, we design an optical comparator for a successive two QPSK symbols. The constellation in each symbol is given in the form of Gray code; their constellations are shown in Fig. 1(c). The most-significant-bit (MSB) and least-significant-bit (LSB) in each symbol contribute to the quadrature-phase and in-phase component in the complex plane, respectively.

The proposed scheme mainly consists of three steps: i) serial-to-parallel (S/P) conversion, ii) phase rotation, and iii) optical coupling. When a 4-bit codeword comprised of a successive two QPSK symbols is given, first, the proposed scheme converts the serially-successive symbol into two parallel symbols. Then, the phases in each symbol are independently rotated to convert their original constellations into a first quadrant in the Gray code, whose position corresponds to a
“00” constellation in Fig. 1(c). Finally, the two phase-shifted symbols are optically coupled. Consequently, the proposed scheme generates a coupled symbol whose constellation is equal to a vector sum of the two “00” symbols; the position is called as a base—constellation in this paper.

For example, we assume that an optical comparator is designed for a “01 10” codeword, which comprises two QPSK symbols; here, it is named as a “01 10” comparator. The phase rotations for the 1st and 2nd symbols are set at $-\pi/2$ and $\pi/2$ to convert their constellations “01” and “10” into “00” and “00”. As an example, when a “01 10” codeword is injected into the comparator, the coupled symbol will be located at the base-constellation due to its design concept: shown in Fig. 1(d)-♯1. Similarly, in the case of “11 11”, “11 01”, and “10 01” codewords, both constellations in “11 11”, “11 01”, and “10 01” are converted into “01” and “10”, “01” and “11”, and “11” and “11” by the phase rotations; the three constellations are shown in Fig. 1(d)-♯2～♯4. As the four constellations are detected at a $\pi/4$ angle with respect to the horizontal axis in the complex plane, the Euclid distances from the base-constellation correspond to the Hamming distances of $d_H(0110,0110) = 0$, $d_H(0111,0110) = 2$, $d_H(1101,0110) = 3$, and $d_H(1001,0110) = 4$, respectively. Therefore, the proposed scheme is able to conform the Euclid distance from the base-constellation to the Hamming distance from the “01 10” codeword; the codeword of comparator is called as a comparator code in this paper.

Fig. 2 indicates an actual configuration of the optical comparator. The comparator is designed for 4-bit codeword comprised of a successive two QPSK symbols, and it consists of an optical delayed interferometer. In the comparator, the successive symbol is equally divided into two parts at a front branch. The one of the parts is relatively separated by one-symbol interval by propagating comparable delay length; therefore, the serially-successive symbol is converted into two parallel symbols in this manner. Then, both phases in each symbol are independently rotated by two phase-shifters. Finally, the two separated symbols are optically coupled at a following branch. Consequently, the comparator creates a coupled symbol from the successive two QPSK symbols. According to the device configuration, it is shown that a comparator code is determined by the phase rotations in each phase shifter. For example, in the case of a “00 00” comparator, the phase rotations for 1st and 2nd symbols are set at 0 and 0. Similarly, a “01 10” comparator sets their phase rotations at $-\pi/2$ and $\pi/2$. Therefore, the proposed comparator is capable of designing for an arbitrary 4-bit codeword to control the phase rotations in each phase shifter.

3. Experimental Setup

3.1 Optical Comparator for 4-bit Codeword

Fig. 3 shows the experimental setup of the proposed optical comparator. In this experiment, the comparator was designed for a 4-bit codeword. The experimental setup mainly consists of three components: namely, a QPSK generator, optical gate, and optical comparator. First, a probe light generated from a tunable laser diode (TLD) emitting at 1550 nm wavelength was QPSK-modulated by using a dual-parallel Lithium-Niobate Mach-Zehnder modulator (LN-MZM) driven by a pulse pattern generator (PPG) with a $2^9 - 1$ pseud random binary sequence (PRBS) at 10.72 GHz. The QPSK-modulated signal was then return-to-zero (RZ)-coded by a 2nd LN-MZM driven by the PPG with a 10.72 GHz clock. Next, the QPSK-modulated RZ signal is injected into a 3rd LN-MZM to
serve as an optical gate. A 200 ps optical gate was created by the 3rd LN-MZM with a 2nd PPG, which corresponds to a time-interval related to a successive two QPSK symbols, and a particular 4-bit codeword was selected from the $2^9 - 1$ PRBS by controlling the position of the gate. Then, the selected two symbols are injected into a following optical comparator. The optical comparator consists of an optical delayed interferometer; the interferometer had one phase shifter. To control a phase rotation of the phase shifter, the first 2-bit of a comparator code can be changed. Finally, the comparator generates a coupled symbol, and the coupled symbol is detected at a following balanced photo detector (BPD).

The author experimentally evaluated the fundamental property of the delayed interferometer. First, an optical pulse was injected into the interferometer. The optical pulse, which had a 9.2 ps of full width at half maximum (FWHM), is generated by a mode-locked laser diode (MLLD) emitting at 1550 nm wavelength. Fig. 4(a) and (b) indicate the input and output pulses of the interferometer. From Fig. 4(b), it can be seen that the interferometer offers a 50:50 branch ratio and 93 ps time-interval, which corresponds to a 10.72 GHz free spectrum range (FSR).

Next, an amplified spontaneous emission (ASE) light was injected into the interferometer. In the experiment, a 0.6 V voltage was applied to a phase shifter in the interferometer. Fig. 4(c) gives the transmission spectra plotted against the light wavelength, and the solid- and dashed-lines correspond to the spectrum obtained from bar- and cross-ports in the interferometer. The bar-port spectra in various phase biases are shown in Fig. 4(d). The spectra are laterally shifted for long-wavelength side with increasing the applied voltage, and the four spectra are arranged at uniform intervals within a single period. Specifically, the phase rotations $0$, $\pi/2$, $\pi$, and $3\pi/2 (-\pi/2)$ are achieved in the condition that the applied voltages were set at 0.6, 1.2, 1.8, and 2.4 V, respectively.

### 3.2 Optical Comparator for 6-bit Codeword

Fig. 3(b) provides the experimental setup of a 6-bit optical comparator. The comparator comprises a serially-cascaded two delayed interferometers; one interferometer had a 10.72 GHz FSR and
the other one had a 5 GHz FSR. In this experiment, the optical gate was extended to 300 ps pulse-width to select a 6-bit codeword, which consists of a successive three QPSK symbols. The 1st and 3rd symbols in the 6-bit codeword are coupled by an added 5 GHz interferometer, then, the coupled symbol and the 2nd symbol are optically overlapped in the following 10.72 GHz interferometer. Consequently, the three QPSK symbols simultaneously overlap each other, and the obtained symbol is detected at a following BPD. In the comparator, the first 4-bit of a comparator code can be changed by controlling two phase-shifters in each interferometer.

The basic properties of the added delayed interferometer were experimentally evaluated. Fig. 5(a) and (b) indicate the impulse response of the interferometer. As can be seen in Fig. 5(b), the interferometer had a 44:56 branch ratio and 199 ps time-duration, which corresponds to a 5.03 GHz FSR. Furthermore, Fig. 5(c) and (d) show the transmission spectra of the interferometer. From Fig. 5(d), it can be seen that the applied voltages of 2.3, 2.8, 3.2, and 3.7 V offered the phase rotations of 0, $\pi/2$, $\pi$, and $3\pi/2$ ($-\pi/2$), respectively.

4. 4-bit Comparison Operation

4.1 Constellations

The author experimentally demonstrated the optical comparison operation for 4-bit codeword of a successive two QPSK symbols. First, we confirm the feasibility of the proposed scheme to generate
the constellation of 4-bit codeword. In this experiment, the four comparators were prepared to adjust applied voltage of a phase shifter in a 10.72 GHz interferometer, whose four comparator-codes of “00 00”, “11 00”, “10 00”, and “01 00” were implemented by the phase rotations of 0, π, π/2, and −π/2, respectively. The eight optical signals, which are related to “00 00”, “11 00”, “10 00”, “01 00”, “11 11”, “00 11”, “01 11”, and “10 11” codewords, were utilized to input the four comparators. Each comparator generates eight constellations obtained from the eight coupled-symbols. In this case, the constellation of the coupled symbol was indirectly estimated. The constellation is given by a vector sum of a constellation of the 1st symbol and a difference vector between the 1st and 2nd symbols. Here, the former was previously evaluated from its QPSK constellation, and the latter, namely, the difference vector, was obtained from a delay detection with a BPD.

Fig. 6(a) shows the generated constellations obtained from the “00 00” comparator. In this figure, the *Hamming* distance of \( d_H(c, 0000) \), where \( c \) is a binary sequence of the given eight codewords, is accurately equal to the *Euclid* distance from the base-constellation; the constellations were detected at a \( \pi/4 \) angle with respect to the horizontal axis in the complex plane. For example, in the case of a “00 00” codeword, the constellation is located at the base-constellation; the *Euclid* distance from the base-constellation corresponds to the *Hamming* distance of \( d_H(0000, 0000) = 0 \). Meanwhile, in the case of “10 00” and “01 00” codewords, their constellations are located at 1-bit length away from the base-constellation, which are equal to \( d_H(1000, 0000) = d_H(0100, 0000) = 1 \). Similarly, the other constellations are located farther away from the base-constellation with increasing \( d_H(c, 0000) \). Furthermore, in the case of “11 11” codeword, the constellation is located at the farthest position:
Fig. 7. Optical waveforms of coupled symbol generated from 4-bit optical comparator: (a1–a8) Temporal waveforms generated from “00 00” comparator with the inputs of “00 00”, “11 00”, “10 00”, “01 00”, “11 11”, “00 11”, “01 11”, and “10 11” codeword, (b1–b8) Temporal waveforms generated from “11 00” comparator with the inputs of “00 00”, “11 00”, “10 00”, “01 00”, “11 11”, “00 11”, “01 11”, and “10 11” codeword, (c1–c8) Temporal waveforms generated from “10 00” comparator with the inputs of “00 00”, “11 00”, “10 00”, “01 00”, “11 11”, “00 11”, “01 11”, and “10 11” codeword, and (d1–d8) Temporal waveforms generated from “01 00” comparator with the inputs of “00 00”, “11 00”, “10 00”, “01 00”, “11 11”, “00 11”, “01 11”, and “10 11” codeword.

$\textit{d}_H(1111, 0000) = 4$. According to the operating principles, it is indicated that the comparator can support a full of 16 possible codewords including other eight codewords, such as “10 10”, “01 01”, “11 10”, . . . , and so on. Therefore, the proposed scheme offers the comparison results of 4-bit codeword based on a “00 00” comparator code.

The constellations obtained from the “11 00”, “10 00”, and “01 00” comparators are shown in Fig. 6(b), (c), and (d), respectively. In this figures, it can be seen that the Hamming distance of $\textit{d}_H(\text{c}, \text{c}_B)$, where $\text{c}_B$ is a comparator code, accurately corresponds to the Euclid distance from the base-constellation in each comparator. For example, in the case of the “11 00” comparator, the constellations whose pattern is similar to “11 00” are located near the base-constellation. In contrast, the constellations having different pattern from “11 00” are located away from the base-constellation. Similarly, the same results were obtained from the “10 00” and “01 00” comparators, respectively. From the above experiments, we confirm the feasibility of the optical comparison operation for 4-bit codeword at 10 Gbaud/s.

4.2 Optical Waveform

Then, the author experimentally evaluated the optical waveform of the 4-bit comparator. In this experiment, the coupled symbol generated from each comparator was overlapped with a $\pi$/4-shifted light, and the constellations shown in Fig. 6(a)–(d) are converted into optical waveforms.

Fig. 7(a1)–(a8) indicate the optical waveforms generated from the “00 00” comparator with the eight inputs of “00 00”, “11 00”, “10 00”, “01 00”, “11 11”, “00 11”, “01 11”, and “10 11” codewords. The center of each waveform corresponds to the coupled symbol, and its signal intensity...
is related to the constellation of the given codeword. Specifically, in this figure, the signal intensity accurately coincide with the Hamming distance of $d_H(c_0000)$. For example, in the case of a “00 00” codeword, the signal intensity has a maximum level and both bit-patterns are completely matched: $d_H(0000, 0000) = 0$. Meanwhile, in the case of “10 00” and “01 00” codewords, their signal intensities go down a notch from their maximum level: $d_H(1000, 0000) = d_H(0100, 0000) = 1$. Similarly, the intensity goes down a notch further with increasing $d_H(c_0000)$. Furthermore, the signal intensity reaches a minimum level with a “11 11” codeword because both bit-patterns are completely different: $d_H(1111, 0000) = 4$.

Fig. 7(b1)–(b8), (c1)–(c8), (d1)–(d8) indicate the signal intensities generated from the “11 00”, “10 00”, and “01 00” comparators. In this figures, it can be seen that the Hamming distance of $d_H(c, c_B)$ is accurately equal to the signal intensity in each comparator. As an example, in the case of the “11 00” comparator, the signal intensities of the “11 00” and “00 11” codewords correspond to their maximum and minimum levels: $d_H(1100, 1100) = 0$ and $d_H(0011, 1100) = 4$. Similarly, as can be seen in Fig. 7(c1)–(c8) and (d1)–(d8), the same results were obtained from the “10 00” and “01 00” comparators, respectively. Therefore, we confirm the feasibility of the 4-bit comparison operation in terms of optical waveform.

### 4.3 BER Evaluation

Then, the author experimentally evaluated the achievable BER of the 4-bit comparator. In this experiment, an ASE light source was added in front of the 4-bit comparator to generate white Gaussian noise. The average power of the ASE light was fixed at $-11$ dBm, and the normalized signal-to-noise ratio (SNR), namely, $SNR_{per\ bit}$, was changed from 9 to 17 dB in various signal powers. In this experiment, the BERs were numerically derived from the measured eye-patterns of the coupled symbol in accordance with a following equation

$$BER = \frac{1}{2}erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{1}{2}erfc\left\{\frac{\mu_i - \mu_0}{\sqrt{2}(\sigma_1 + \sigma_0)}\right\},$$

where $\mu_i$ and $\sigma_i$ ($i = 0$ or 1) are the average power and standard deviation in the obtained eye. The subscripts of $i$ correspond to the “0-level” and “1-level” of the coupled symbol, additionally, $Q$ and $erfc()$ are a Q-factor and complementary error function.

Fig. 8 shows the derived BERs plotted against the SNR per bit. The solid and dashed lines provide the theoretical BER curves of the proposed scheme and QPSK modulation, respectively. In the proposed scheme, the minimal distance $d_{min}$ is given by $d_0/\sqrt{2}$, where $d_0$ is a minimal distance of QPSK constellation; the solid line, therefore, shifts a 3 dB to the high-SNR side. In Fig. 8,
5. 6-bit Comparison Operation

The author experimentally demonstrated the optical comparison operation for 6-bit codeword of a successive three QPSK symbols. In this experiment, the six comparators for the comparator codes
of “00 00 00”, “01 00 00”, “11 00 00”, “11 10 00”, “11 01 00”, and “11 11 00” were prepared by adjusting applied voltages of each phase shifter in the 5.03 and 10.72 GHz interferometers. The twelve patterns of optical signal were input into the comparators, which are related to the codewords of “00 00 00”, “00 00 11”, “00 01 01”, “10 00 01”, “01 01 01”, “10 10 01”, “10 10 10”, “01 11 10”, “11 11 00”, “11 10 10”, and “11 11 11”, respectively.

Fig. 9(a) indicates generated constellations obtained from the “00 00 00” comparator. From Fig. 9(a), it can be seen that the constellations to be similar to a “00 00 00” codeword are located near the base-constellation, and the constellations to be different from the “00 00 00” codeword are located away from the base-constellation. In the condition that the constellation was detected at $\pi/4$ angle with respect to the horizontal axis, the Euclid distance from the base-constellation is accurately equal to the Hamming distance from the “00 00 00” comparator code. Similarly, Fig. 9(b), (c), (d), (e), and (f) provide the constellations obtained from the “01 00 00”, “11 00 00”, “11 10 00”, “11 01 00”, and “11 11 00” comparators, respectively. The constellations in Fig. 9(b)-(f) indicate that every comparator offers the constellations excellently reflected with a similarity between a given codeword and comparator code: same as the “00 00 00” comparator. Therefore, we experimentally confirm the feasibility of the optical comparison operation for 6-bit codeword at 10 Gbaud/s.

6. Discussion
The discussion will focus on the expandability of the proposed optical comparator to other modulation formats and codeword lengths. The proposed scheme is based on three steps: i) S/P conversion, ii) phase rotation, and iii) optical coupling. Here, focusing on the phase rotation, it is considered that the proposed scheme can be extended to rotationally-symmetric modulations, such as BPSK and 16PSK, since all constellations in the modulations are allowed to exchange each position by phase rotation; to be more precise, it is necessary that their constellation is given in the form of a Gray code. Furthermore, focusing on the optical coupling, it is considered that the proposed scheme has a linearity for their codeword lengths, since optical coupling provides a vector sum of each symbol in a complex plane. Therefore, the proposed scheme can be adapted to an arbitrary length, such as 8-bit, 10-bit, 12-bit, ..., and more. Taking into consideration the points mentioned above, it is concluded that the proposed optical comparator can provide highly extensible operation for their modulation formats and codeword lengths.

7. Conclusion
As a summary, this paper has given a feasibility demonstration of optical comparison operation for 4-bit and 6-bit PSK-modulated signals. First, we experimentally investigated the performance of a 4-bit optical comparator. The 4-bit comparators designed for “00 00”, “11 00”, “10 00”, and “01 00” codewords were implemented by using an optical delayed interferometer, which had a 50:50 branch ratio and 10.72 GHz FSR in our experiment. A 4-bit codeword, which is comprised of a successive two QPSK-modulated RZ symbols at 10.72 Gbaud/s, was utilized to input into each comparator, and each comparator generates the constellation of the 4-bit codeword. In this experiment, it is indicated that the constellation is located at the position reflected in conformity with a Hamming distance between a given codeword and a comparator code; additionally, same operation is achieved in the condition that the constellation was converted into an optical waveform. Furthermore, the noise effect of the comparator was experimentally evaluated, and it is indicated that the comparator can offer their theoretical BER. Then, we experimentally investigated the performance of a 6-bit optical comparator. The comparator consists of a serially-cascaded two delayed interferometers; one interferometer had a 10.72 GHz FSR and the other one had a 5.03 GHz FSR. The six comparators were designed for “00 00 00”, “01 00 00”, “11 00 00”, “11 10 00”, “11 01 00”, and “11 11 00” codewords, and a successive three QPSK symbols at 10.72 Gbaud/s was utilized to input into each comparator. In this experiment, it is shown that the Euclid distance of the constellation is accurately equal to their Hamming distance in each comparator.
From above results, it is concluded that the proposed scheme can offer a comparison operation for 4-bit and 6-bit codewords at 10 Gbaud/s.

Acknowledgment

The authors would like to thank Prof. H. Uenohara of Tokyo Institute of Technology for assistance with the experimental installation and helpful discussions.

References