Numerical Analysis of Dither Induced Penalty for Automatic Bias Control Methods

Jinyang Wu, Linsheng Zhong, Xiaoxiao Dai, Qi Yang, Mengfan Cheng, Lei Deng, and Deming Liu

***Abstract*—The Mach-Zehnder modulator (MZM) is widely used in high-speed optical communication, and the stability of its bias point is the key to maintain the performance of the communication system. Numerous automatic bias control methods have been proposed to stabilize the bias point, which can be classified into power-based and dither-based methods. The power-based method features low-complexity and is considered of low-precision, thus it is usually applied to low-order modulation. In contrast, dither-based method features high-complexity and is considered of high-precision, therefore it is usually applied to high-order modulation. This paper explores the bias impact mechanism and analyzes the impact of the bias and dither signal. Traditional view is that the performance of dither-based outperforms power-based ones. However, the impact of dither is ignored. Here we compare the performance of the power-based and dither-based method under fair conditions. The results show that the power-based method has higher SNR and better performance taking into account the impact of dither, which indicates that practically it is more suitable for high-order modulation.**

***Index Terms*—Bias control, MZM, coherent communication.**

I. Introduction

Modern optical communication system is developing to even larger capacity building on high-order modulation and large-bandwidth signal. As a key component in electro-optical conversion, the Mach-Zehnder modulator (MZM) featuring large bandwidth, high-order modulation loading ability, zero chirp, and simple structure, is the most versatile and widely used device. For the best performance of the transmission, MZM needs to be set at corresponding bias points for different modulation formats. However, the optimum bias point will drift due to environmental factors such as fluctuations of temperature, humidity, and stress [1]. It will degrade the SNR and affect the quality of transmission over long-time operation. Thus, it is necessary to conduct automatic bias control (ABC) to stabilize the bias point.

Numerous ABC methods have been proposed, which can be generally classified into power-based and dither-based methods. The simplest power-based method uses the DC power and AC power of the MZM output for feedback control [2]. The dither-based methods uses an extra dither signal which is a periodic perturbation of the bias to manually generate more information for feedback control. For power-based method, statistical data after analog-to-digital converter (ADC) can be used for simplifying the structure [3]. The derivative information can be used for any bias point control [4]. The neural network can also be applied to detect the bias state [5], [6], [7]. All the power-based methods utilize the information of DC and AC in different ways. However, the control logic is relevant to modulation format and the precision is considered not enough for high-order modulation, then the dither-based method is deployed. The harmonic information of the dither can be used for feedback control [8]. The most common dither signal is the sine signal. The square signal can be used to reduce complexity [9]. Linear-frequency modulated signal can alleviate the penalty of the dither with the cost of complexity [10]. The lock-in amplifier and filter are used to extract the harmonic information [11], [12]. Later the correlation method has been proposed to simplify the complexity [13]. The frequency of the dither is usually a few kHz or tens of kHz to avoid the 1/f noise, but over GHz dither is also effective [14], [15]. High frequency dither increases the structure complexity of ABC, thus it is rarely used in industry. Most methods will add dither signal to bias-I and bias-Q port, but there is also 3 dithers method applied to all bias ports to enhance the precision of bias-P [16]. However, the dither on bias-P will cause a big penalty. Besides the basic feedback control, other techniques such as Kalman filter can be combined to improve the performance [17].

Generally, the power-based methods have less complexity and are considered of lower precision, thus they are usually applied to low-order modulation such as QPSK, because this scenario is more tolerant to bias drift but is more sensitive to cost and complexity [2]. On the contrary, the dither-based methods are generally more complex and are considered of higher precision, therefore they are mostly applied to high-order modulation because this scenario is more sensitive to precision. However, these general judgements ignore two aspects of consideration. On the one hand, the hardware difference in practical implementation is ignored. To generate a dither signal, the dither-based methods need higher sample rate ADC which will increase the SNR for

Manuscript received 30 August 2023; revised 19 November 2023; accepted 28 November 2023. Date of publication 4 December 2023; date of current version 29 December 2023. This work was supported in part by the National Natural Science Foundation of China under Grants 62205115 and 62275091, and in part by the Innovation Project of Optics Valley Laboratory under Grant OVL2021BG002. *(Corresponding author: Xiaoxiao Dai.)*

Jinyang Wu, Linsheng Zhong, Mengfan Cheng, Lei Deng, and Deming Liu are with the School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: jinyangwu@hust.edu.cn; zhonglinsheng@hust.edu.cn; chengmf@mail.hust.edu.cn; denglei_hust@mail.hust.edu.cn; dmliu@hust.edu.cn).

Xiaoxiao Dai and Qi Yang are with the School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China, and also with Optics Valley Laboratory, Wuhan 430074, China (e-mail: daixx@hust.edu.cn; yangqi@hust.edu.cn).

Digital Object Identifier 10.1109/JPHOT.2023.3338617

© 2023 The Authors. This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

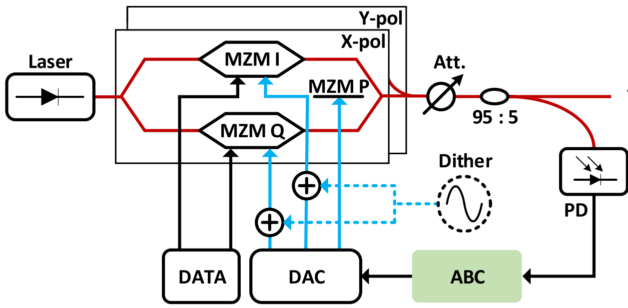

Fig. 1. Schematic diagram of a basic ABC scheme.

ABC (ABC-SNR) by bringing more information. The power-based methods can be easily supported by low-cost hardware, which will deteriorate the ABC-SNR. On the other hand, the dither impact on signal quality is ignored. The dither signal is superimposed on the bias port, then it will cause the periodic variation of the bias point. The constellation point of signal will vary too. The interval of constellation point is smaller for high-order modulation, therefore the impact is larger.

So far, there is no detailed analyses about the dither impact on different modulation formats. In this paper, we explore the bias impact mechanism and analyze the impact of the bias and dither signal. We conduct a fair comparison between the power-based and dither-based methods based on the same condition. The results show that dither-based method with 5% V_π dither or larger will have better performance ignoring the dither impact. However, when the dither impact is considered which is closer to the actual situation, dither-based method will have a great performance degradation for high-order modulation, and power-based method will have better performance. The estimated precision for 64QAM is 1.66% V_π.

The remainder of this paper is organized as follows. In Section II, the theoretical model of a MZM is introduced, based on which the bias impact mechanism is analyzed. In Section III, the impacts of the bias and dither are numerically analyzed. In Section IV, performances of the power-based and dither-based methods are compared. Finally, Section V draws the conclusion.

II. System Model

A. The Structure of ABC

The general structure of IQ-MZM is shown in Fig. 1. IQ-MZM is composed of 2 MZMs, MZM-I and MZM-Q. Each MZM has two ports. One is a high-speed radio frequency (RF) port for loading RF data for transmission, the other is a low-speed bias port for bias control. There are 3 biases for IQ-MZM to control, bias-I, bias-Q, and bias-P. Bias-I and bias-Q are similar, adjusting the working point of MZM-I and MZM-Q. Bias-P adjusts the orthogonality between the two MZMs. After coupler, the modulated light is exported. A 10% or 5% tapper will be used to tap out a small portion of the light for feedback control following the IQ-MZM output. The feedback light passes through a low bandwidth photodetector (PD), being sampled by a low sample rate ADC. The sampled data are fed to the ABC module for updating the bias state. Finally, the updated bias is conveyed to each bias port by the digital-to-analog converter (DAC) to finish the feedback control. The dither-based method will have a dither generator. Now the dither signal is mostly generated in the digital domain before DAC and then superimposed to the newest bias value. That means the structure of the dither-based method is similar to the power-based. The main difference is the ABC algorithm. The power-based method directly reacts to the optical power. The dither-based method needs to obtain the harmonics information by filtering or correlating the optical power, and then conduct the feedback control.

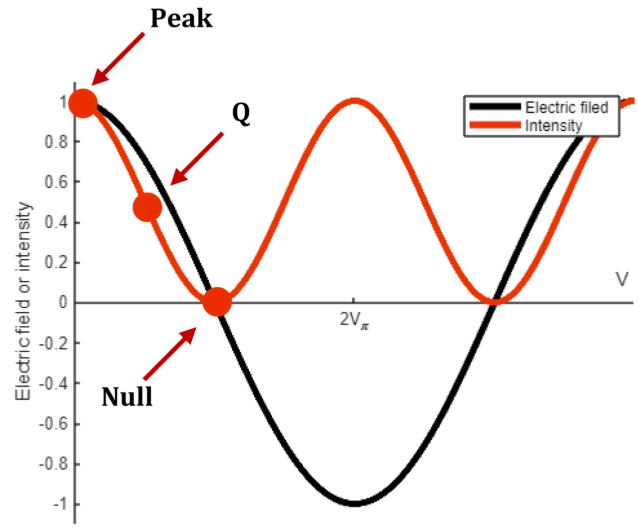

Fig. 2. Modulation curve of MZM.

B. Mathematic Analysis of MZM and Bias Impact

For a single MZM, the output electric field is

$$E_{out} = E_{in} \cdot \cos\left(\frac{V}{2V_\pi}\pi\right) \tag{1}$$

where E_{in} and E_{out} are the electric field of the MZM's input and output light respectively, V is the loading voltage, and V_π is the half-wave voltage. As mentioned above, the loading voltage is comprised of RF data V_s and bias voltage V_b, and $V = V_s + V_b$, providing

$$\begin{aligned} E_{out} &= E_{in} \cdot cos\left(\frac{V_b + V_s}{2V_\pi}\pi\right) \\ &= E_{in}\left[cos\left(\tfrac{V_b}{2V_\pi}\pi\right) cos\left(\tfrac{V_s}{2V_\pi}\pi\right) \right. \\ &\quad \left. - \sin\left(\frac{V_b}{2V_\pi}\pi\right)\sin\left(\frac{V_s}{2V_\pi}\pi\right)\right] \end{aligned} \tag{2}$$

Presume no data is modulated at the MZM, $V_s = 0$, we can draw the modulation curve of the MZM as shown in Fig. 2. There are several bias points in common use, peak, Q, and Null point. The peak point corresponds to the maximum optical power, the null point corresponds to the minimum optical power, and the Q point also known as the 3 dB point corresponds to the half of maximum optical power. The null point is used to generate BPSK, QPSK, or high-order QAM format. The Q point is used to generate OOK or high-order PAM format. The coherent technique is widely used, and the order of modulation is becoming higher. Therefore the null point ABC is important. When the bias is ideally set to null point, $V_b = V_\pi$, according to (2), we can obtain the output of the MZM

$$E_{out} = -E_{in} \cdot \sin\left(\frac{V_s}{2V_\pi}\pi\right) \quad (3)$$

Since the modulation curve of MZM is nonlinear, when the modulation depth increases, the nonlinearity will increase. To maximize the utility of the MZM's extinction ratio (ER), nonlinear-predistortion can be deployed to V_s for compensating the nonlinearity. $f_L(\cdot)$ represents the operation of nonlinear-predistortion. The mathematical expression is $f_L(x) = \arcsin(\frac{x}{V_\pi} \cdot \frac{\pi}{2})$, so we have $\sin(\frac{f_L(V_s)}{2V_\pi}\pi) = \frac{V_s}{V_\pi}$. After linearization, the output of MZM becomes

$$\begin{aligned} E_{out} &= -E_{in} \cdot \sin\left(\frac{f_L(V_s)}{2V_\pi}\pi\right) \\ &= -E_{in} \cdot \frac{V_s}{V_\pi} \end{aligned} \quad (4)$$

The bias will drift away from the ideal point due to the change of environmental factors. Assuming that the bias voltage V_b deviate ΔV_b from the ideal point, and using the relationship of nonlinear-predistortion $\sin(\frac{f_L(V_s)}{2V_\pi}\pi) = \frac{V_s}{V_\pi}$, we can obtain the actual output of the MZM

$$\begin{aligned} E_{out} = &-E_{in} \cdot \left[\sin\left(\frac{\Delta V_b}{2V_\pi}\pi\right)\cos\left(\frac{f_L(V_s)}{2V_\pi}\pi\right)\right. \\ &\left. + \cos\left(\frac{\Delta V_b}{2V_\pi}\pi\right) \cdot \frac{V_s}{V_\pi}\right] \end{aligned} \quad (5)$$

There are two more factors compared to (4). The factor $\cos(\frac{\Delta V_b}{2V_\pi}\pi)$ will reduce the amplitude of the signal, which decreases the SNR of the MZM output. The factor $\sin(\frac{\Delta V_b}{2V_\pi}\pi)\cos(\frac{f_L(V_s)}{2V_\pi}\pi)$ is composed of two parts, the former is determined by the deviation, and the latter will cause the offset of the constellation point. The offset is not equal for each constellation point. Larger signal has smaller offset while smaller signal has larger offset, which causes nonlinearity. The constellation diagram seems like being pulled from the middle to the side. As a result, the distance between the constellation points is not equal anymore. One side will expand out and the other side will squeeze together. Thus the deviation of the bias will distort the constellation diagram and cause performance degradation.

C. Basic Algorithm of ABC and Simulation Parameter

Power-based method detects the DC and AC components of the optical power. For a single MZM or bias-I and bias-Q of an IQ-MZM, the calculating coefficient of ABC is

$$C_{power} = \langle I_{PD} \rangle \quad (6)$$

where I_{PD} is the current signal of the low bandwidth PD, $\langle\cdot\rangle$ represents the average operation. The control method adjusts the bias until the C_{power} reach the maximum or minimum. As for the bias-P, the AC component is detected, because the AC power will increase when the orthogonality is broken [2].

Dither-based method generates and sends a dither to MZM, and detects the harmonic component. Correlation is a common way to analyze the harmonic component, the calculating coefficient is

$$C_{dither} = \langle I_{PD} \cdot V_d \rangle \quad (7)$$

where V_d is the dither signal. The correlation of PD signal and dither is equivalent to the average of the product that PD signal multiply the dither. It is similar to (6) but has a frequency shift. The control method adjusts the bias until C_{dither} reaches zero. The digital dither that is used in correlation needs to be in phase with the analog dither that is output to the bias port for maximum performance. As for bias-P, the sum frequency component of bias-I dither and bias-Q dither is analyzed for feedback control.

This paper sets up the simulation based on the mathematic model of modulator and ABC basic algorithm, and co-simulates with MATLAB and VPIphotonics. The simulation parameters are shown in Table I. The baud rate of RF data is set to 40 GBaud or 10 GBaud. Modulation format is QPSK, 16QAM, 64QAM and 256QAM. Modulation depth is 100%. The predistortion is deployed to linearize the MZM. Simulation length is 2^{17} symbol. The data sampling time of a single feedback control is 13.1072 μs. The bandwidth of the narrow bandwidth PD is 200 MHz and the sample rate of the PD is 625 MSa/s. Dither is sine signal with 50 MHz frequency and 1% V_π, 5% V_π, 10% V_π amplitude. The practical bandwidth and sample rate of a PD are usually smaller. Increasing the sample rate can reduce simulation time. The practical dither frequency is usually smaller such as several kHz or tens kHz. Increasing the frequency can also reduce the simulation time. We shall prove that dither signal within 100 MHz is equivalent in a system in which the RF data is the main noise for ABC. The other noise such as the hardware noise and PD noise can be ignored because these noises are relatively small and are different for each board and device.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Baud rate	40GBaud or 10GBaud
Modulation format	QPSK, 16QAM, 64QAM, 256QAM
Modulation depth	100%
Symbol length	2^17
Sampling time	13.1072 µs
PD bandwidth	200 MHz
PD sample rate	625MSa/s
Dither frequency	50 MHz
Dither amplitude	1% V_π, 5% V_π, 10% V_π

III. Bias and Dither Impact

In this section, the impact of bias and dither is analyzed for several modulation formats. The penalty of bias and dither is

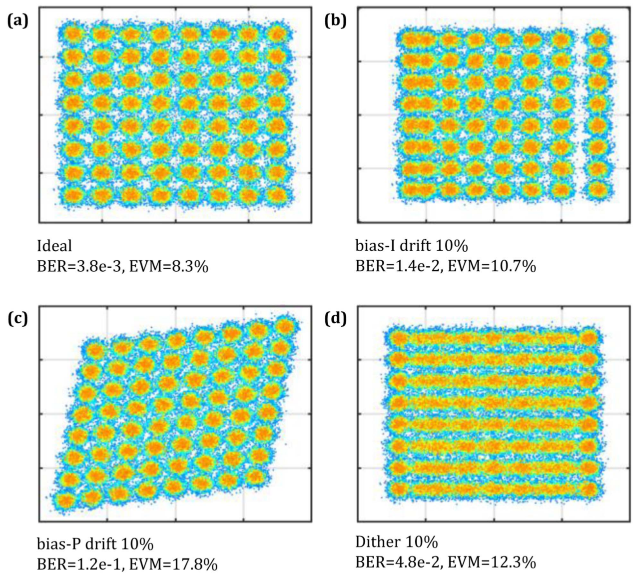

Fig. 3. Influence of bias and dither to 64QAM. (a) Ideal constellation; (b) 10% V_π bias-I drift; (c) 10% V_π bias-P drift; (d) 10% V_π dither impact.

similar which means that the dither is an equivalent bias shift in some way.

An ideal constellation of a 40 GBaud 64QAM format and the distorted constellations caused by bias drifts and dither insertion are shown in Fig. 3. The frequency offset and linewidth of laser are ignored to demonstrate the pure influence of the bias and dither. The OSNR is set to 30.3 dB by adding amplifier spontaneous emission (ASE) noise. When the bias is set to the ideal point, i.e., bias-I and bias-Q is set to V_π, bias-P is set to $\frac{V_\pi}{2}$, the ideal constellation is shown in Fig. 3(a), the bit error ratio (BER) is 3.8e-3, which is the threshold of the 7% overhead hard-decision FEC (HD-FEC), and the error vector magnitude (EVM) is 8.3%. The bias-I impact of 10% V_π drift is shown in Fig. 3(b), the bias-P impact is shown in Fig. 3(c), the dither impact is shown in Fig. 3(d). Since bias-I and bias-Q are equivalent, the impact of bias-Q is not discussed independently. The direction of bias-I and bias-P drift in Fig. 3 is upward, and the situation of downward drift is similar. The performance influence is the same and the constellation diagram is the left and right flip of Fig. 3(b) and (c). When bias-I drifts 10% V_π, the BER is up to 1.4e-2 and EVM is 10.7%. The constellation is damaged, the linearity is broken, and the distance between the constellation point is not equal anymore. The point is closer at left half and is more dispersed at right half, which is in accordance with the theoretical analyses by (5). The impact is only in the I direction because the bias drift is applied to bias-I. The situation of bias-P is different as shown in Fig. 3(c). The constellation is still a uniform space however the shape is changed from a square to a rhombus. The reason is that bias-P affects the orthogonality which will induce the crosstalk of RF data between I and Q channel. It will bring severe degradation. The BER and EVM for bias-P is 0.12 and 17.8% which is worse than bias-I.

When we discuss the performance of dither-based method, the stability of bias attracts more attention, but the dither impact is usually ignored. Fig. 3(d) is the constellation of ideal bias point with 10% V_π dither impact. The offset of constellation point is similar to the situation of bias-I drift. The difference is that the offset will vary with time due to the existence of dither. According to (5), the direction and amplitude of the offset will change with the dither signal, leading to the broadening of the constellation point to overlaps. The point suffers severe impact in the middle area and mild impact in the margin area. And larger dither cause larger impact. The impact is only in I direction because only bias-I port is superimposed with dither. The BER and EVM are 4.8e-2 and 12.3%. For 64QAM, the impact of dither is larger than bias-I and smaller than bias-P with the same amplitude.

The OSNR curve for QPSK, 16QAM, 64QAM, 256QAM under the impact of 5% V_π bias-I, bias-P drift and dither is shown in Fig. 4(a), the 10% V_π situation is shown in Fig. 4(b). For the same impact such as bias-I, the performance degradation becomes larger when the order of modulation increases. Bias or dither within 10% V_π has little influence on QPSK, but large influence on high-order format such as 256QAM, for which even the FEC limit cannot be reached. With the existence of 10% V_π bias drift or dither, the OSNR for ideal 256QAM transmission can only support 64QAM, leading to the waste of the power budge. Fig. 4(c) draws the detail for OSNR curve of 16QAM, 64QAM and 256QAM under the impact of bias and dither from 0% V_π to 10% V_π. Left is the impact of bias-I, middle is the impact of bias-P and right is dither. When the amplitude of bias or dither increases, the curve of OSNR will become flat, resulting in unavoidable degradation. It is more obvious in high-order modulation such as 64QAM. The reason is the existence of errors when the constellation points overlap or the shape distortion of the constellation diagram as shown in Fig. 3. Higher order modulation reaches the flat area more quickly, which means that the impact of bias drift and dither increase with order increase. This paper uses the 3.8e-3 BER threshold which corresponds to 7% overhead HD-FEC as baseline. However, for a smaller BER baseline, the degradation of bias and dither is more severe.

For better comparison, we calculate the penalty based on the BER threshold. The penalty of bias-I, bias-P and dither are shown in Fig. 5(a)–(c) respectively. QPSK can suffer a large bias drift and dither. There are less than 3 dB penalty of bias-I and dither with 60% V_π drift or amplitude, and bias-P with 20% V_π drift. However, for high-order modulation, the penalty increases rapidly. There exists a limit for bias drift, beyond which the penalty becomes very large and brings the system performance to an unacceptable degradation. The limit for bias drift is lower for high-order modulation. For example, the limit is about 5% V_π for 256QAM bias-I drift as shown in Fig. 5(a). To numerically analyze the limits of different modulation, we define the bias threshold, which is the corresponding bias drift of 6 dB penalty. The thresholds of bias-I, bias-P and dither are shown in Table II. This limit can give guidance that how large dither can be applied and what ABC precision is required for different modulation formats. It is worth noting that 256QAM has a very small range for permissible bias drift and dither. If we used the dither-based method to conduct ABC for 256QAM, the amplitude of dither

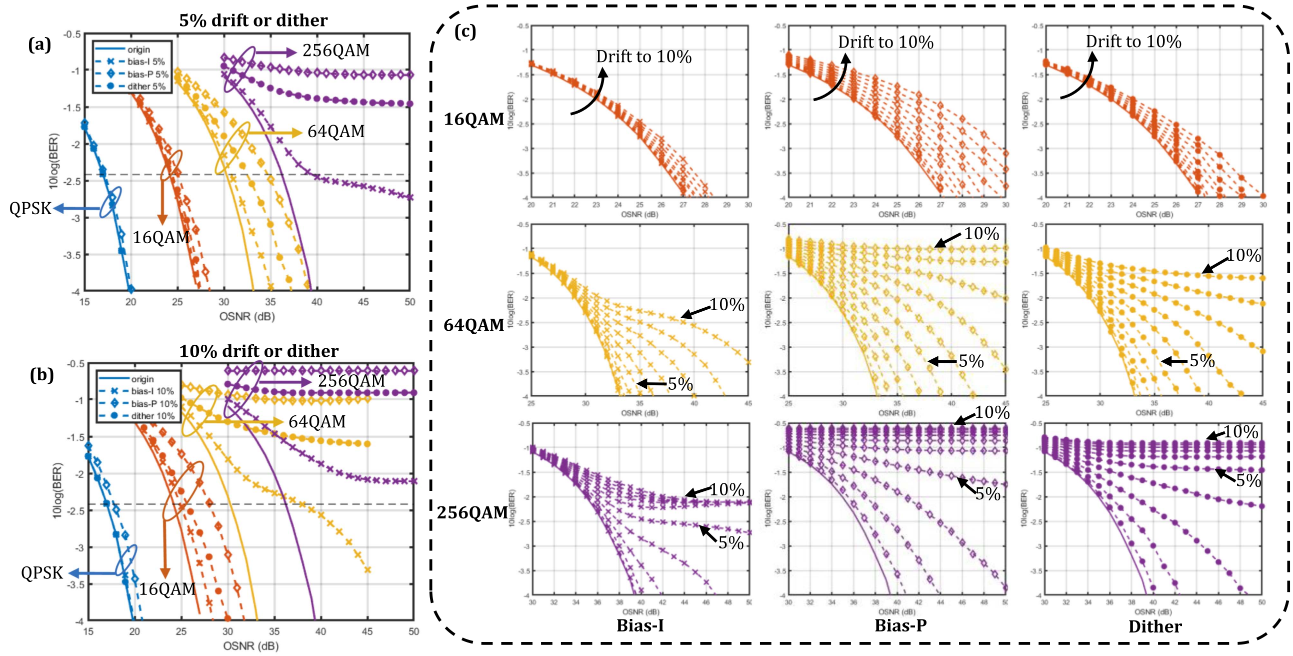

Fig. 4. OSNR curve of the impact of bias and dither.

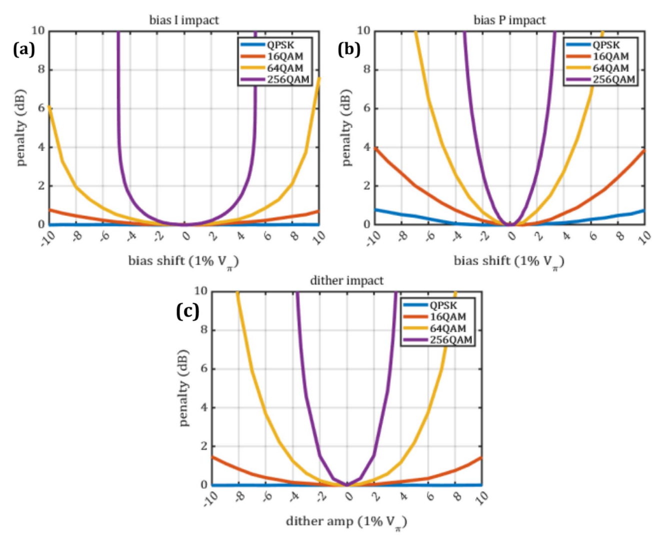

Fig. 5. Penalty of bias and dither.

should be smaller than 3.2% V_π. However, the performance of dither-based method is relevant to dither amplitude. Therefore it will cause a difficulty to apply dither-based method for high-order modulation format.

The comparison of penalty between bias-I, bias-P and dither is shown in Fig. 6. The bias-P is always the maximum impact. The dither impact is closer to bias-P when the modulation order increases. For 16QAM and higher order format, dither impact is always larger than bias-I. It means that the dither will create an equivalent bias drift even if the bias point is optimum. Therefore, the dither impact should not be ignored.

TABLE II
THRESHOLD FOR 6 dB PENALTY

(Unit: V_π)	**Bias-I**	**Bias-P**	**Dither**
QPSK	69.3%	29.3%	81.0%
16QAM	22.1%	12.2%	16.1%
64QAM	9.8%	5.7%	7.0%
256QAM	5.1%	2.8%	3.2%

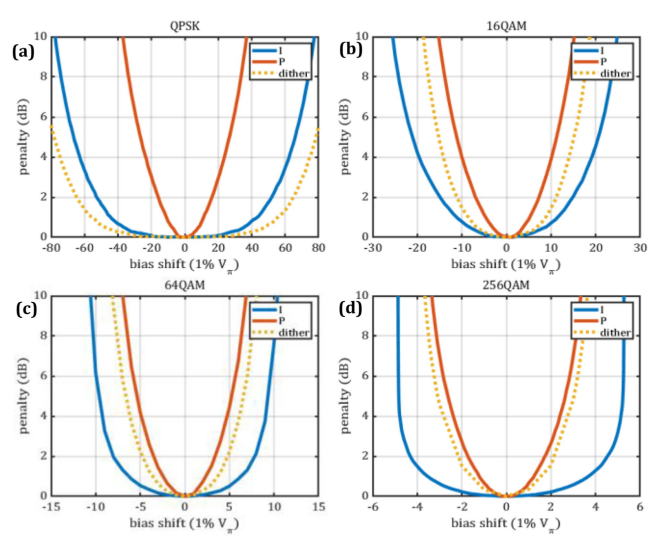

Fig. 6. Penalty comparison under different modulation formats.

Furthermore, to obtain the influence of bias with communication digital signal processing (comm-DSP), we add the commonly used multi-modulus algorithm (MMA) for equalization,

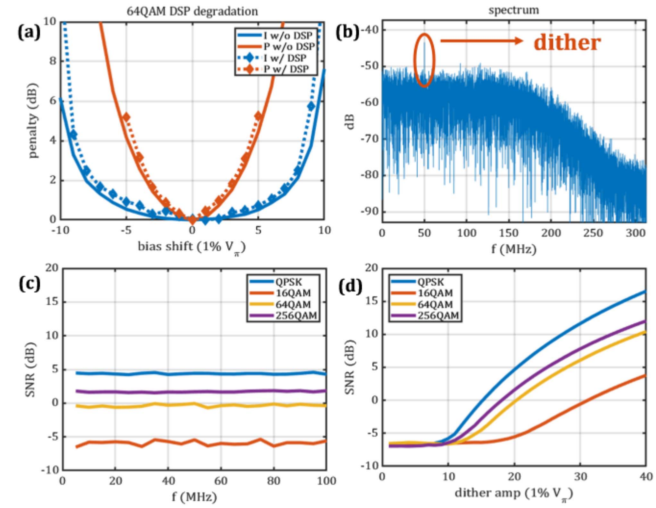

Fig. 7. (a) Influence of bias on comm-DSP. (b) Spectrum of PD when deploying the dither-based method. (c) Dependence of the dither SNR about frequency. (d) Dependence of the dither SNR about amplitude.

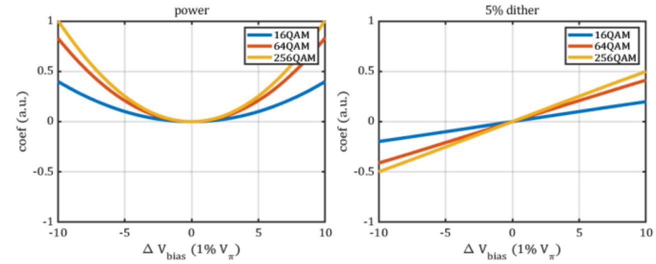

Fig. 8. Sensitivity of power-based and dither-based method.

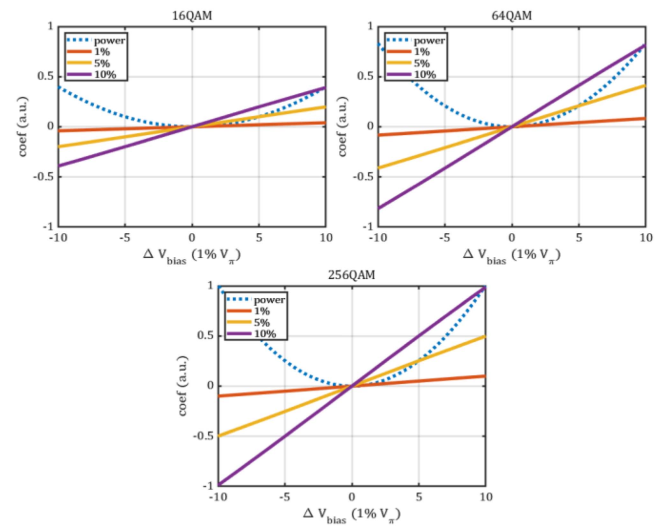

Fig. 9. Sensitivity of different modulation formats.

FFT-based estimator for carrier frequency recovery (CFR), and blind phase search (BPS) for carrier phase recovery (CPR). The result is shown in Fig. 7(a). Dotted line is the penalty with comm-DSP. It shows that comm-DSP does not help with bias drift. The degradation slightly increases and the bias threshold is more clear. To focus on pure bias impact, the residue simulations remove the comm-DSP.

Generally, dither frequency is several kHz or tens kHz. Higher frequency requires high sample rate ADC and DAC which increase the cost of hardware. The 50 MHz dither signal is deployed to reduce the simulation time. The spectrum of the low bandwidth PD output is shown in Fig. 7(b). We test the dither SNR with different frequency. The noise calculated bandwidth of dither SNR is 5 MHz. The result is shown in Fig. 7(c). The dither SNR is independent of dither frequency within 100 MHz. The fluctuation, which is introduced by the RF data which is the main noise for ABC, is small enough compared to the SNR change with different dither amplitude as shown in Fig. 7(d). Thus the 50 MHz dither is equivalent to several kHz dither. Actually there is 1/f noise in the hardware and the higher frequency dither will experience less 1/f noise. But the RF data is the dominating noise. Different modulation format leads to different RF data noise level to ABC, which is also shown in Fig. 7(c). 16QAM has the maximum impact and QPSK has minimum impact.

IV. Performance Comparison

In this section, we fairly compare the performance of power-base and dither-based ABC method. The RF data signal is 10 GBaud 16QAM, 64QAM and 256QAM signal. The bandwidth of the low bandwidth PD is 200 MHz and the sample rate of the PD is 625 MSa/s. Sampling time for each feedback control is 13.1072 us.

The sensitivity is a key parameter to represent performance. Sensitivity is defined as the slope of calculating coefficient of ABC C_{power} and C_{dither}, which is the change of calculating coefficient when the bias changes a unit. Fig. 8 shows the sensitivity of power-based (left figure) and dither-based method (right figure). The amplitude is normalized together. The dither amplitude is set to 5% V_π for dither-based method. The target of power-based method is to make the C_{power} to minimum point. The target of dither-based method is to make the C_{dither} to zero. The sensitivity varies with the modulation format. 256QAM has the maximum sensitivity and 16QAM has the minimum sensitivity. The sensitivity will increase with the increase of modulation order. Both methods have these characteristics. The reason is that the sensitivity of C_{dither} is originated from the dither frequency component, which comes from the power fluctuation of MZM output with bias fluctuation. The change of MZM output power versus bias can be approximated as a modulation curve of a sine form. This relation suffers from the noise of RF data. When the relation becomes weaker such as in the 16QAM, sensitivity of both methods will decrease. This relation is not only affected by modulation format but also the shaping and modulation depth. There exists a case that the relation is very weak that the MZM output power will not change if the bias changes. This may happen when the QPSK modulation depth is less than 100%. In this situation, both ABC methods will fail.

A more comprehensive comparison of the sensitivity for different format is shown in Fig. 9. Dotted line is the sensitivity of power-based method, solid line is the sensitivity of dither-based

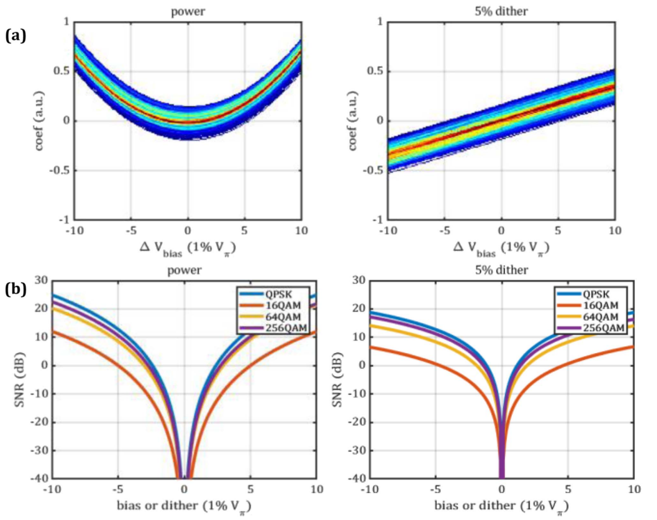

Fig. 10. (a) Calculating coefficient with the noise. (b) ABC-SNR of power-based and dither-based method.

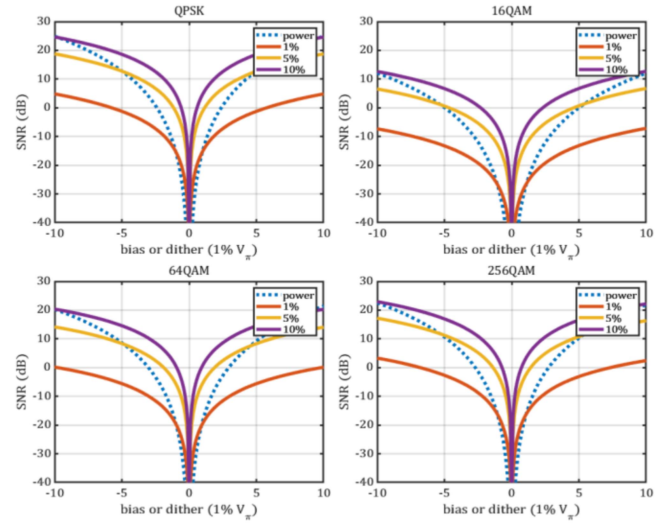

Fig. 11. ABC-SNR comparison between power-based and dither-based method without consideration of dither penalty.

method with 1%, 5%, 10% V_π dither. The common opinion is dither-based method has higher sensitivity. But we find that it is not absolute. The situation is different for different bias area. The sensitivity will become larger with larger bias drift for power-based method and keep constant for dither-based method. Thus in a small bias drift, i.e., the dither area, the dither-based outperforms power-based, and in a large bias drift, i.e., the power area, the power-based outperforms dither-based. The larger amplitude of dither gains larger sensitivity. The boundary of dither area and power area is related to dither amplitude. For example, the boundary of 1% V_π dither is just about 1% V_π. That means if we want dither-based method to outperform more, the dither amplitude must be increased, which will cause the increase of penalty.

After loading the RF data with 100% modulation depth, the calculating coefficient is shown in Fig. 10(a). We conduct 1000 independent simulations for each bias point to analyze the influence of RF data. We introduce ABC-SNR to describe the performance of ABC. The ABC-SNR for power-based method is calculated by

$$ABC\_SNR\left(\Delta V_b\right) = \frac{\sum\left(\overline{C}_{power,\Delta V_b} - \overline{C}_{power,0}\right)^2}{\sum\left(C_{power,\Delta V} - \overline{C}_{power,\Delta V}\right)^2} \quad (8)$$

where $C_{power,\Delta V_b}$ is the C_{power} at the bias point that drifts ΔV_b from the optimum point, and $\overline{C}_{power,\Delta V_b}$ is the average of coefficient. The ABC-SNR is shown in Fig. 10(b). The calculation of ABC-SNR for dither-based method is similar. For both ABC methods, maximum ABC-SNR can be obtained for QPSK, and minimum for 16QAM. It is similar to sensitivity.

ABC-SNR for different modulation format is shown in Fig. 11. The dotted line is the SNR for power-based method and solid line is for dither-based method. The result is consistent with sensitivity in Fig. 9. In the small bias drift area, i.e., the dither area, the ABC-SNR for dither-based method is higher,

TABLE III
DITHER PENALTY

(Unit: dB)	Dither amplitude (V_π)		
	1%	**5%**	**10%**
QPSK	0.01	0.01	0.02
16QAM	0.03	0.27	1.45
64QAM	0.07	2.21	>10
256QAM	0.35	>10	>10

and in the larger bias drift area, i.e., the power area, the situation is reversed. The boundary of dither area and power area is approximately equal dither amplitude. Dither-based method improves the ABC-SNR in dither area at the cost that decreases the ABC-SNR in power area. It would be a better method if the dither impact is ignored.

However, the dither impact will become huge for high-order modulation. According to the simulation result in Section III, the penalty of dither is shown in Table III. Though dither-based method with 5% V_π, 10% V_π dither have better performance than power-based method in a large dither area, 5% V_π dither will bring obvious penalty for 64QAM and 256QAM. We give the dither an equivalent bias drift based on the penalty for different modulation format. The equivalent bias drift of dither is larger than bias-I of the same amplitude in high-order QAM format as discussed above. And the dither area is approximately the amplitude. Thus the equivalent bias drift will fill the dither area and the advantage of dither-based method is lost. The result is shown in Fig. 12. The power-based method has the higher ABC-SNR while taking into account the dither impact. The advantage becomes even evident when the order of modulation increase.

The ABC-SNR affects the distinction of the calculating coefficient. We take a couple of bias point, one is the optimum point, and the other is the bias point that drift until the ABC-SNR reach 0 dB or 10 dB. The probability distribution of the calculating

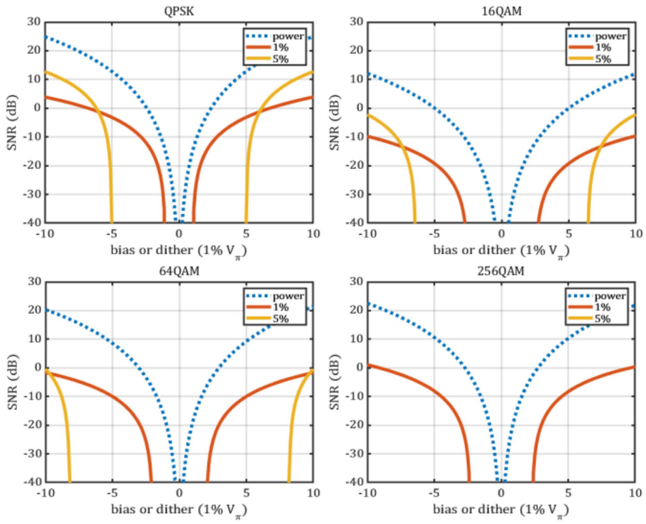

Fig. 12. ABC-SNR comparison considering dither penalty.

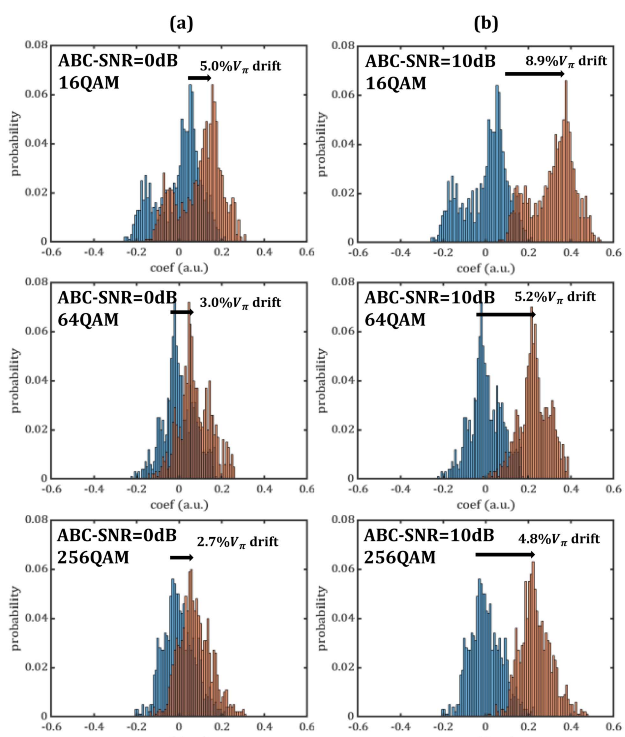

Fig. 13. Precision with different ABC-SNR.

coefficients of these couple bias point is shown in Fig. 13. The 10 dB ABC-SNR is enough to distinguish the calculating coefficient precisely. There is some overlap which will cause the error recognition at 0 dB ABC-SNR. Therefore we take 10 dB ABC-SNR as the reference of estimated precision. The bias drift is slow, thus the sample length for a single feedback control can be increased to hundreds of ms. Our result is based on the sample length of 13.1072 μs, therefore the ABC-SNR can be improved by about 40 dB. If the ADC sample rate is decreased to 6.25 MSa/s to reduce cost, the ABC-SNR will lose about 20 dB. Therefore the overall potential ABC-SNR improvement is 20 dB. Thus we can take the -10 dB ABC-SNR as the reference of estimated precision. The result is shown in Table IV while the dither impact is ignored. The performance of power-based method is better than dither-based method of 1% V_π dither and worse than 5% V_π dither. Though the estimated precision for large dither is very high, the dither impact is huge for high-order modulation turning the main problem from bias stabilization to dither penalty. The high precision is useless. Considering the dither impact, the power-based method will be better and is more suitable for high-order modulation such as 64QAM and 256QAM.

TABLE IV
ESTIMATED PRECISION

(Unit: V_π)	Power-based	Dither-based		
		1%	**5%**	**10%**
QPSK	1.35%	1.83%	0.37%	0.19%
16QAM	2.82%	7.20%	1.47%	0.73%
64QAM	1.66%	3.00%	0.60%	0.29%
256QAM	1.54%	2.22%	0.44%	0.23%

This paper only focuses on the main noise of RF data. There exists 1/f noise and other noise in the hardware. The 1/f noise in low frequency will be slightly larger, therefore the power-based method suffers more noise than dither-based method. However, it is relatively small when compared to RF data noise. The actual performance gap between the power-based and dither-based method will be slightly smaller than the result.

V. CONCLUSION

This paper explores the bias impact mechanism and analyzes the impact of the bias and dither. The performances of the power-based and dither-based ABC methods are compared under fair conditions. The results show that bias-P impact is the largest among these biases and dither. Dither impact is less than bias-I impact for QPSK and larger than bias-I for 16QAM, 64QAM, and 256QAM. The dither impact is closer to bias-P impact when the high-order modulation format is applied. The bias threshold is the corresponding bias drift of 6 dB penalty. The bias-I threshold for QPSK, 16QAM, 64QAM, 256QAM is 69.3%, 22.1%, 9.8%, 5.1% V_π respectively, bias-P is 29.3%, 12.2%, 5.7%, 2.8% V_π and dither is 81.0%, 16.1%, 7.0%, 3.2% V_π. If the dither impact is ignored, 5% V_π and 10% V_π dither methods outperform the power-based method. However, dither impact on high-order modulation increases rapidly, causing a remarkable equivalent bias drift. Taking into account the dither impact, the power-based method has better performance. The estimated precision of power-based method is 1.35% V_π, 2.82% V_π, 1.66% V_π, 1.54% V_π for QPSK, 16QAM, 64QAM, 256QAM respectively. In a practical system, the variation in ADC sample rate, sample length, noise of hardware, and noise of PD will result in changes of the estimate precision.

REFERENCES

[1] J. P. Salvestrini, L. Guilbert, M. Fontana, M. Abarkan, and S. Gille, "Analysis and control of the DC drift in LiNbO3Based Mach–Zehnder modulators," *J. Lightw. Technol.*, vol. 29, no. 10, pp. 1522–1534, May 2011, doi: 10.1109/JLT.2011.2136322.

[2] P. S. Cho, J. B. Khurgin, and I. Shpantzer, "Closed-loop bias control of optical quadrature modulator," *IEEE Photon. Technol. Lett.*, vol. 18, no. 21, pp. 2209–2211, Nov. 2006, doi: 10.1109/LPT.2006.884759.

[3] P. S. Cho and M. Nazarathy, "Bias control for optical OFDM transmitters," *IEEE Photon. Technol. Lett.*, vol. 22, no. 14, pp. 1030–1032, Jul. 2010, doi: 10.1109/LPT.2010.2049198.

[4] X. Yuan, Y. Zhang, J. Zhang, and M. Zhang, "Any point bias control technique for MZ modulator," *Optik*, vol. 178, pp. 918–922, Feb. 2019, doi: 10.1016/j.ijleo.2018.10.091.

[5] H. Pang, Q. Zhu, S. An, J. Li, and Y. Su, "Flexible bias control for a Mach-Zehnder modulator based on a two-layer neural network algorithm," in *Proc. IEEE Asia Commun. Photon. Conf.*, Chengdu, China, 2019, p. M4A.14.

[6] J. Wu et al., "A ditherless bias control technique for IQ Mach-Zehnder modulator based on partial derivative and neural network," in *Proc. IEEE Asia Commun. Photon. Conf.*, Shanghai, China, 2021, p. M5H.6.

[7] J. Wu et al., "Neural network assisted ditherless bias control for optical IQ modulator using relative detection," in *Proc. IEEE Conf. Lasers Electro-Opt.*, San Jose, CA, USA, 2022, p. SW4E.6.

[8] J. Svarny and S. Chladek, "Model-based bias controller for a Mach-Zehnder intensity modulator," *J. Lightw. Technol.*, vol. 40, no. 3, pp. 720–727, Feb. 2022, doi: 10.1109/JLT.2021.3122460.

[9] H. Li et al., "Simple and ultrafast automatic bias control for optical IQ modulators enabled by dither vector mapping monitoring," in *Proc. IEEE Opt. Fiber Commun. Conf. Exhib.*, San Diego, CA, USA, 2022, p. Th1C.7.

[10] Z. Pan et al., "Arbitrary bias point control for Mach-Zehnder modulator using a linear-frequency modulated signal," *IEEE Photon. Technol. Lett.*, vol. 33, no. 11, pp. 577–580, Jun. 2021, doi: 10.1109/LPT.2021.3075453.

[11] H. Kawakami, E. Yoshida, and Y. Miyamoto, "Auto bias control technique based on asymmetric bias dithering for optical QPSK modulation," *J. Lightw. Technol.*, vol. 30, no. 7, pp. 962–968, Apr. 2012, doi: 10.1109/JLT.2012.2184261.

[12] T. Gui et al., "Auto bias control technique for optical OFDM transmitter with bias dithering," *Opt. Exp.*, vol. 21, no. 5, pp. 5833–5841, Mar. 2013, doi: 10.1364/OE.21.005833.

[13] X. Li et al., "Modulation-format-free and automatic bias control for optical IQ modulators based on dither-correlation detection," *Opt. Exp.*, vol. 25, no. 8, pp. 9333–9345, Apr. 2017, doi: 10.1364/OE.25.009333.

[14] Z. S. Al-Aubaidy, "Bias control of the IQ optical modulator using side pilot-tone in optical OFDM transmitters," *IEEE Photon. Technol. Lett.*, vol. 25, no. 24, pp. 2419–2422, Dec. 2013, doi: 10.1109/LPT.2013.2287704.

[15] X. Li et al., "Arbitrary bias point control technique for optical IQ modulator based on dither-correlation detection," *J. Lightw. Technol.*, vol. 36, no. 18, pp. 3824–3836, Sep. 2018, doi: 10.1109/JLT.2018.2851568.

[16] S. M. Bilal and G. Bosco, "Automatic bias control of Mach—Zehnder modulators for QPSK and QAM systems," *J. Opt. Technol.*, vol. 81, no. 7, pp. 403–407, Jul. 2014, doi: 10.1364/JOT.81.000403.

[17] W. Gao, G. Ge, L. Yang, D. Lu, J. Huo, and X. Zhou, "Kalman filter-based auto bias controller (KF-ABC) for IQ modulator," in *Proc. IEEE Opto-Electron. Commun. Conf.*, Hong Kong, China, 2021, p. W4B.1.