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Bit Error Rate Monitoring for Automatic Bias Control of Quadrature Amplitude Modulators

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***Abstract*—**The most common quadrature amplitude modulator (QAM) applies two Mach-Zehnder Modulators (MZM) and one phase shifter to generate high order modulation format. The bias of MZM changes over time due to temperature, vibration, and aging factors. The change in the biasing causes distortion to the generated QAM signal which leads to deterioration of bit error rate (BER) performance. Therefore, it is critical to be able to lock MZM's Q point to the required operating point for good performance. We propose a technique for automatic bias control (ABC) of QAM transmitter using BER measurements and gradient descent optimization algorithm. The proposed technique is attractive because it uses the pertinent metric, BER, which compensates for bias drifting independently from other system variations such as laser source output power. The proposed scheme performance and its operating principles are simulated using OptiSystem simulation software for 4-QAM and 16-QAM transmitters.

***Keywords*—**Automatic bias control, optical fiber communication, optical modulation, optical devices.

I.INTRODUCTION

THE demand on high data rate communication systems has been growing exponentially due to the emergence of bandwidth-hungry applications such as online gaming and video conferencing [1], [2]. Optical QAM transmitter is required to accommodate this huge demand on bandwidth due to its high spectral efficiency. The most common QAM modulator is IQ modulator which applies two MZMs and one phase shifter [3]. The MZMs need to be biased properly to generate the required QAM signal. For instance, the two MZMs need to be biased at the quadrature point in order to generate 4-QAM signal, also known as QPSK signal. The bias of IQ modulator changes over time due to temperature, vibration, and aging factors [4]. The change in the biasing causes distortion to the generated QAM signal which leads to deterioration of the BER performance. Therefore, it is critical to be able to lock the MZMs Q point to the required operating point for good performance.

Two main techniques for ABC have been widely investigated. The first technique focuses on measuring the output optical power to control the biasing of the MZMs [6]. The optical power is continuously measured, and the variation of the optical power is used to control the biasing voltages. Despite of the simplicity of this technique, it has low sensitivity to acquire for the biasing point especially for low optical power [5], [6]. Also, it is not easy to distinguish the MZM that caused the power variation. Furthermore, the output optical power could change due to other factors such as the variation of optical laser source power. The second technique adds low frequency continues wave RF signal, known as dither signal, to the bias voltage of the MZMs [7], [8]. The power of the second harmonic of the dither signal is used as a control signal to compensate for the bias drifting. Even though the dither signal monitoring technique eliminates the system dependency on the output optical signal, the amplitude of the dither is generally small in order not to affect the RF signal, so the amplitude of the required harmonics especially the second-order harmonic is too small to detect and is easily to be masked by the noise from the hardware [8]-[11].

We propose ABC of QAM transmitter using BER measurements and gradient descent optimization algorithm. The proposed technique uses the pertinent metric, BER, which compensate for bias drifting independently from other system variations such as laser source output power. The proposed scheme performance and its operating principles are simulated using OptiSystem simulation software for 4-QAM and 16-QAM transmitters.

The rest of this paper is organized as follows: Section II describes the operating principles. Section III illustrates the system operation for 4-QAM and 16-QAM transmitters, Section V concludes the paper.

II.OPERATING PRINCIPLE

The configuration of the proposed ABC scheme is shown in Fig. 1. As can be seen, 10% of the output signal from the IQ modulator ($10\%P_o$) is sent to the coherent receiver that comprises 90 degrees hybrid mixer, photo detectors, amplifiers for the in-phase (I) and quadrature (Q) signals, analog to digital converter (ADC) and decision circuit. The local oscillator for the receiver is 10% of the transmitter local oscillator ($10\%P_L$).

The data at the output of the ADC and decision block in the coherent receiver are converted to serial data stream using parallel to serial converter (P/S) and forwarded to BER detector that compares the received data against the transmitted data and determines the BER. Since the coherent receiver is directly connected to the transmitter, the BER should be small (ideally zero). However, due to the laser and photodetectors noise, a small value of BER should be acceptable. Any value higher than that is due to the biasing errors.

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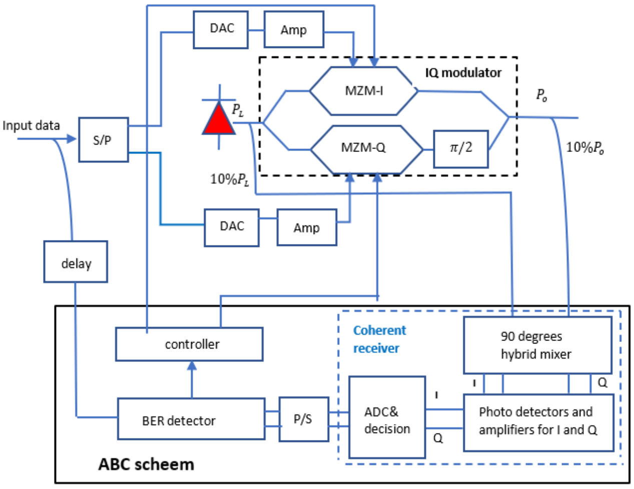


Fig. 1 The proposed ABC scheme based on BER detection

The controller uses gradient descent optimization algorithm to find the optimum values for the biasing voltages for I, Q modulators and phase shifter (V_I, V_Q, and $V_{shifter}$) that leads to minimum BER. The initial values for the algorithm will be the actual measured values of V_I, V_Q, and $V_{shifter}$. The algorithm simply measures the change in BER with respect to the change in the three biasing voltages and lock the voltages to the values that result in minimum BER. The gradient descent converges when the measured BER reaches the lowest value possible. The algorithm steps can be summarized as follows:

Step1. Measure the values of V_I, V_Q, and $V_{shifter}$ and set them as initial weights for the algorithm then measure BER at the output of the transmitter.

Step2. Calculate the gradients through calculating the sum of square errors (SSE) between BER measured in step 1 and BER when weights V_I, V_Q, and $V_{shifter}$ are changed by a small value, called learning rate. This helps us move the values of weights in the direction in which SSE is minimized.

Step3. Adjust the voltages with the gradients to reach the optimal values where SSE is minimized.

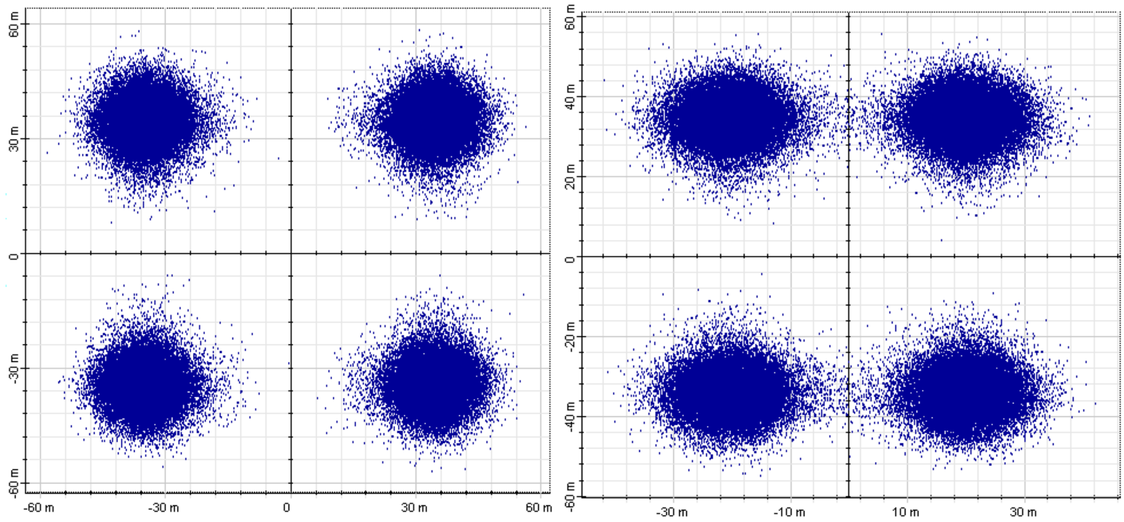
Step4. Use the new voltages for prediction and to calculate the new SSE.

Step5. Repeat steps 2 and 3 till gradient descent converges when BER reaches the lowest value possible.

III. Simulation Results

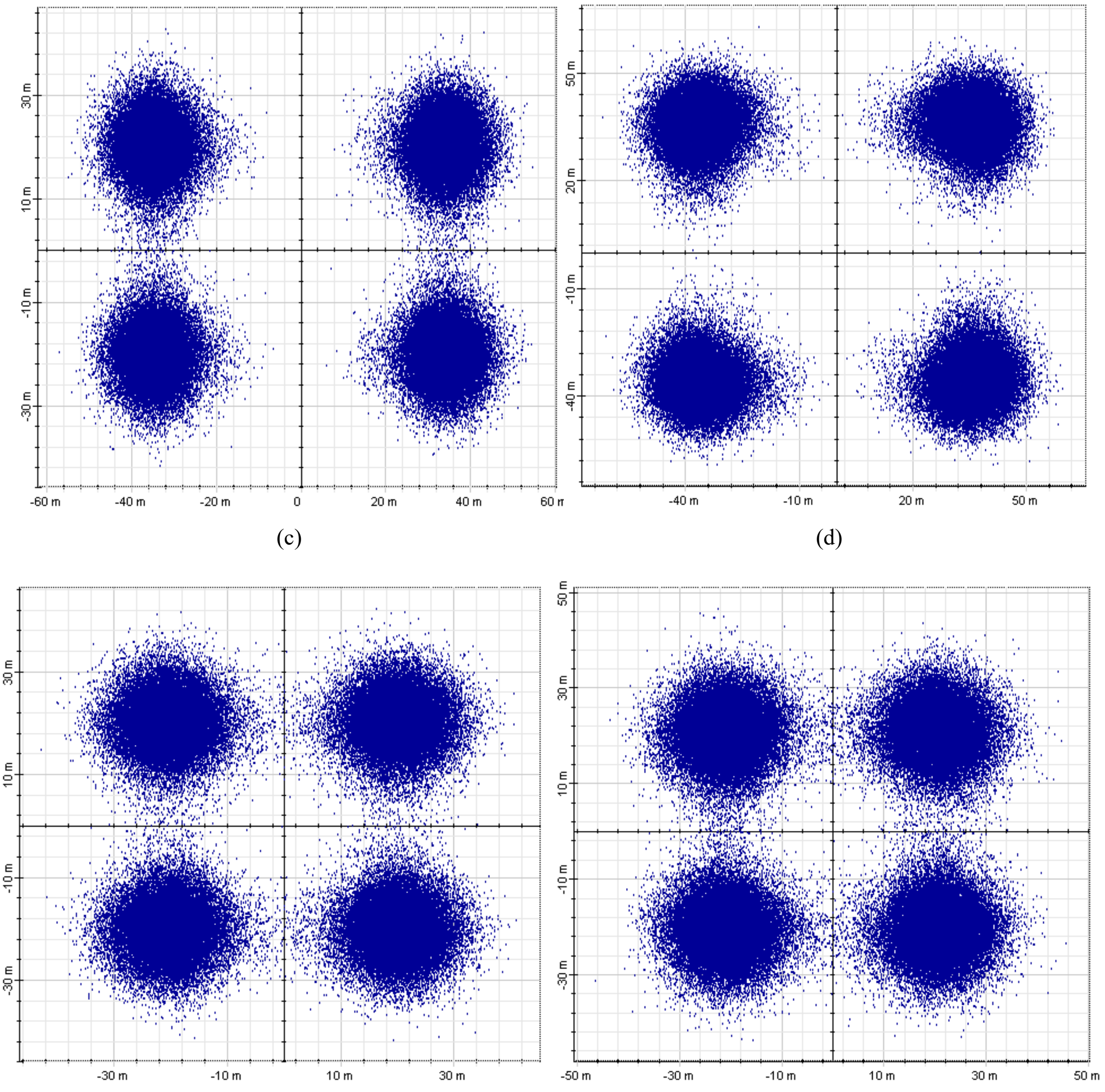
The proposed scheme was simulated using OptiSystem simulation software for both 4-QAM and 16-QAM modulators. The I and Q modulators are biased at the null point with biasing voltages of 3 V. Also 1.5 V was applied to the phase shifter to obtain 90-degrees phase shift. White Gaussian Noise (WGN) was added at the coherent receiver so that the BER under no biasing errors is set to 10^{-5}. The constellation diagram at the output of the 4-QAM modulator under no biasing errors is shown in Fig. 2 (a). As can be seen, the constellation points are equally spaced with no distortion and the measured BER is 10^{-5} as expected. Decreasing the biasing V_I by 1 V leads to decrement of the real component of the constellation point thus shifting of the constellation points closer to the Q-axis as depicted in Fig. 2 (b). On the other hand, decreasing the biasing voltage V_Q by 1 V leads to decrement of the imaginary component of the constellation point thus shifting of the constellation points closer to the Q-axis as seen in Fig. 2 (c). Errors in V_{shifer} by 5 degrees will cause constellation rotation as can be seen in Fig. 2 (d). Errors in both V_I and V_Q will worsen the effect of biasing errors as can be seen from Fig. 2 (e) where the constellation points are shifted closer to I and Q axes. The effect is even worse when V_I and V_Q are change by 1 V and phase shifter introduces 5 degrees phase error as depicted in Fig. 2 (f).

Fig. 3 displays a 3D plot of the BER versus biasing errors of I and Q modulators at 18 dB Eb/No. The graph shows that the BER reaches its minimum (10^{-5}) at zero biasing errors and increases with the biasing errors as expected. The color map inset indicates that a BER of 10^{-4} can be achieved at V_I and V_Q errors of ± 0.6 V if no phase errors are introduced.



(a)

(b)



(c) (d)

(e) (f)

Fig. 2 4-QAM constellation for: (a) no biasing errors; (b) 1V biasing error in the I modulator; (c) 1 V biasing error in the Q modulator; (d) 5 degrees error in phase shifter; (e) 1V error in both I and Q modulators; (f) 5 degrees error in phase shifter and 1 V error in I and Q modulators

To test the ability of the gradient descent optimization algorithm in controlling biasing errors, an error of 1 V was applied to the biasing voltage V_I. The initial values for biasing voltages V_I, V_Q and $V_{shifter}$ were set to 2 V (1 V error), 3 V (no error) and 1.5 V (no error) respectively. After 10 iterations, the algorithm was able to find the optimum biasing voltage V_I that leads to minimum BER of 10^{-5}. 1 V of biasing error was applied to V_I and V_Q so that the biasing voltages are 2 V instead of 3 V, and no error is applied to the phase shifter. After 50 iterations, the controller in the proposed scheme was able to automatically converge to V_I and V_Q of 3 V at BER of 10^{-5}. As can be seen, the number of iterations before error detection increased as compared to the previous scenario when biasing error was applied to I modulator only. Through applying errors to the modulators and to the phase shifter, we noticed that the number of iterations before the algorithm converges increases to 200. The convergence time also increases when error value increases. For instance, the number of iterations when errors of 1 V are applied to both I and Q modulator was 50 iteration while the number of iterations increased to 73 when errors of 1.5 V are applied. Another important parameter is the initial value of the learning rate which must be set to an appropriate value. If the value is too high, the steps the algorithm takes are too big and it may not reach the local minimum because it bounces back and forth around the minimum BER value. If the learning rate is set to a very small value, gradient descent will eventually reach the local minimum but that may take a while.

The proposed ABC scheme was simulated for 16-QAM transmitter. Noise was added to the system so that the BER under no biasing error is set to 10^{-5}. The constellation at the output of the 16-QAM modulator under no biasing error is shown in Fig. 4 (a). Similar to 4-QAM, error of 0.1 V in V_I shifts the constellation closer to Q axes while error of 0.1 V in V_Q shifts the constellation closer to I axes as depicted in Figs. 4

(b) and (c) respectively. 5-degrees error in $V_{shifter}$ would cause constellation rotation as depicted in Fig. 4 (d). Errors in V_I and V_Q shifts the constellation points closer to both I and Q axes as illustrated in Fig. 4 (e). The constellation distortion is even worse when 0.1 V errors are introduced to V_I and V_Q and 5 degrees to $V_{shifter}$ as shown in Fig. 4 (f).

Fig. 5 displays a 3D plot of the BER versus biasing errors of I and Q modulators at 24 dB Eb/No. The graph shows that the BER reaches a minimum (10^{-5}) at zero biasing errors and increases with the biasing errors as expected. The color map inset indicates that a BER of 10^{-4} can be achieved for phase errors of ± 0.05 V if no phase errors are introduced. Comparing Figs. 3 and 5, it is clear that 16-QAM is very sensitive to biasing errors as compared to 4-QAM modulator.

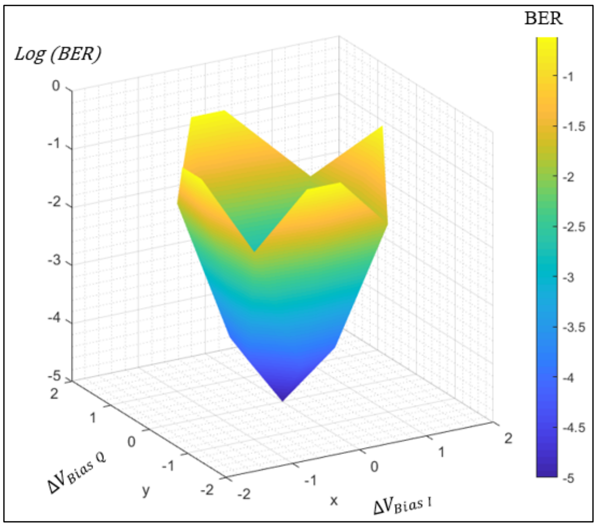
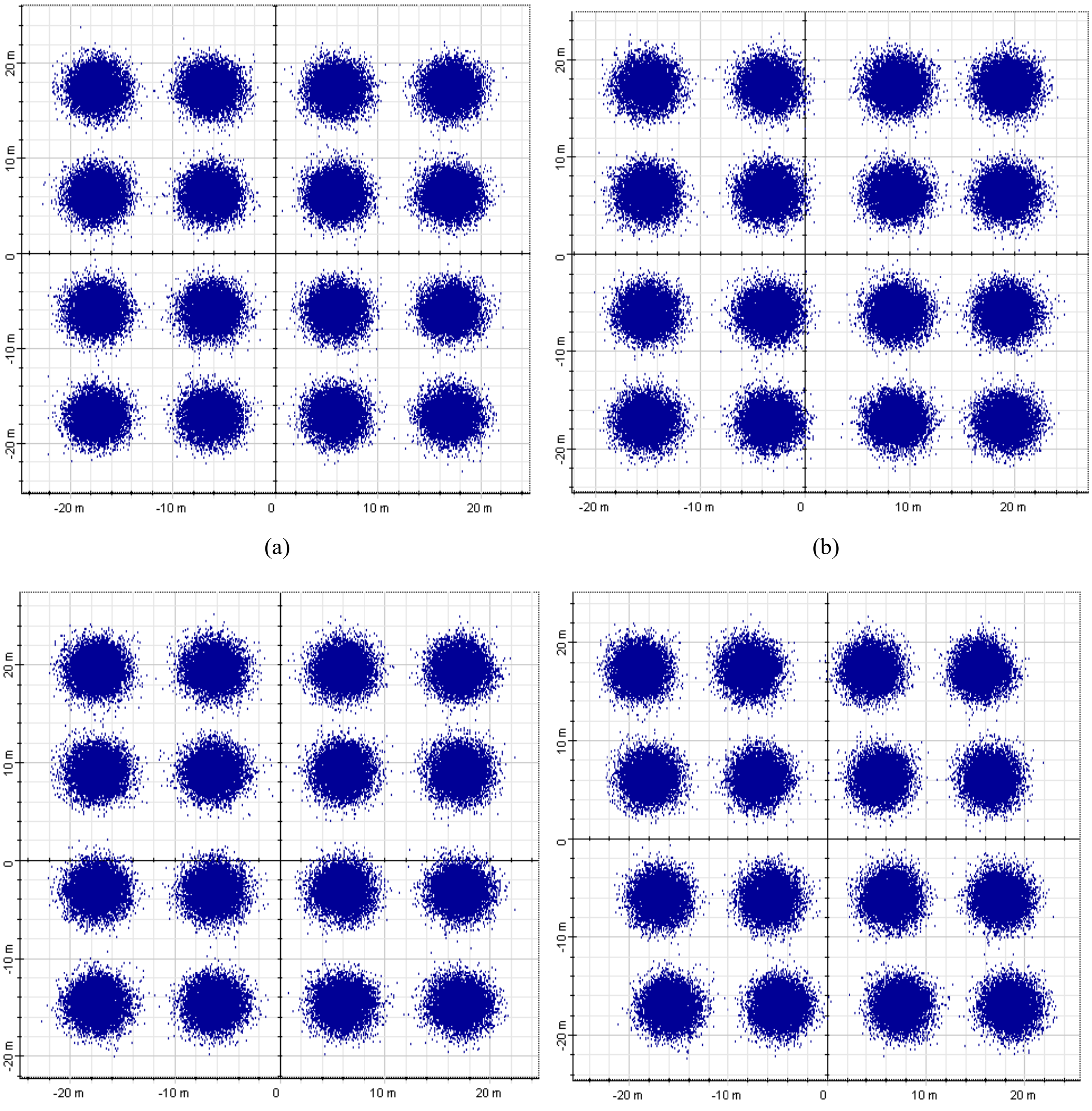


Fig. 3 BER versus change in biasing voltages for I and Q modulators in 4-QAM

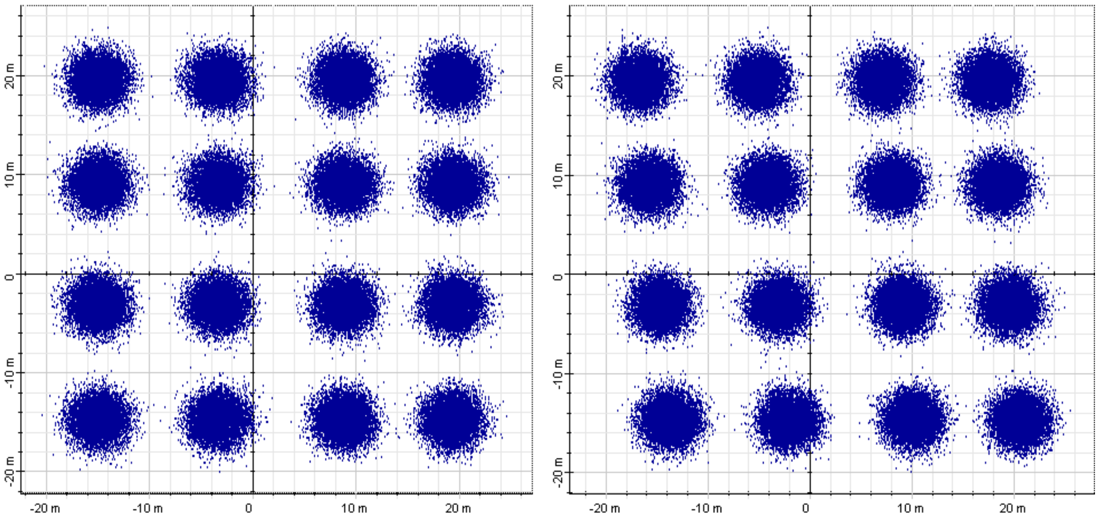


(a)

(b)

(c)

(d)



(e) (f)

Fig. 4 16-QAM constellation for: (a) no biasing errors; (b) 0.1 V biasing error in the I modulator; (c) 0.1 V biasing error in the Q modulator; (d) 5 degrees error in phase modulator; (e) 0.1 V error in both I and Q modulators; (f) 5 degrees error in phase modulator and 0.1 V errors in both I and Q modulators

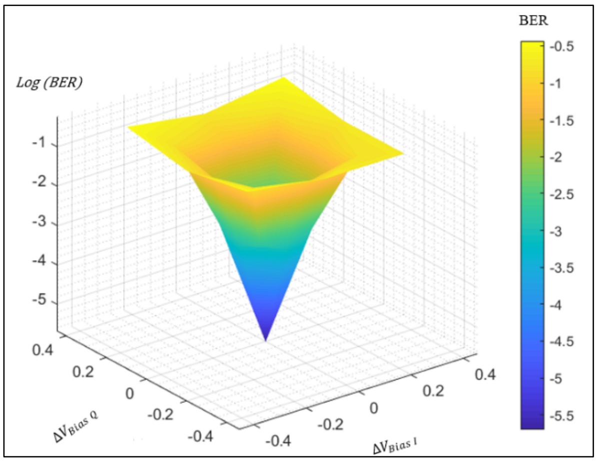


Fig. 5 BER versus change in biasing voltages for I and Q modulators in 16-QAM

The ability of gradient descent optimization algorithm in controlling biasing errors was tested by introducing 0.1 V of error to V_I, and V_Q and 5 degrees error to $V_{shifter}$ following the scenarios used for simulating 4-QAM. Similar to 4-QAM, the controller was able to coverage to the lowest value of BER with almost the same number of iterations. However, the learning rate should be less than 0.01 V to avoid BER values and cause degradation to the system performance.

IV. CONCLUSION

We have presented the design analysis and performance simulation of ABC system that uses BER measurements and gradient descent optimization algorithm to compensate for bias drifting errors for 4-QAM and 16-QAM transmitters. The simulation results showed that the biasing errors would cause constellation distortion and BER degradation. The proposed ABC ensures that the biasing voltages are adjusted so that the transmitter performs at the lowest BER possible. The design analysis and performance simulation can be extended to higher-order modulation format such as 64-QAM and 1024-QAM.

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