

Non-Cubic Eightfold Constellation for High-Performance Stokes Vector Modulation

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Abstract: A novel non-cubic constellation for eightfold Stokes vector modulation improves modulation loss, link budget, and intersymbol interference at high speed, while using simpler drive signals. Experiments confirm 5.2 dB improvement at 30 Gb/s. © 2022 The Author(s)

1. Introduction – Optical links within large data centers require massive data throughput, implemented with low-cost and low-power hardware, prompting research into formats such as Stokes vector modulation (SVM), which can provide a 3-dimensional symbol space with direct-detection receivers [1-4]. Within the 3-dimensional Stokes space, rectilinear constellations, such as cubic 8-SVM, are usually studied [5]. Although Morsy-Osman et al. [6] have investigated non-rectilinear constellations, they did not address the practical implementation issues of modulation loss and intersymbol interference (ISI).

The only commercially-available, integrated solution to generate arbitrary SVM is the cascaded Mach-Zehnder modulator (MZM) developed for (coherent) polarization-multiplexed QPSK (PM-QPSK) links. However, when these integrated modules are used to generate cubic 8-SVM, they incur a large modulation loss which detracts from the link loss budget. Quaternary drive signals with unequally-spaced levels are also needed [7]. In this paper, we introduce a new 8-SVM constellation, generated using simple bias points and just 3 binary drive signals, which we call the Phi constellation. When the Phi constellation is generated by an integrated PM-QPSK module, the modulation loss is 2.6 dB less than the modulation loss for cubic 8-SVM. Furthermore, the Phi constellation reduces the penalty from intersymbol interference (ISI), leading to even greater benefits when high symbol rates are used.

2. 8-SVM Constellation Design - The integrated PM-QPSK module comprises two branches, providing the X-polarized and Y-polarized components of the SVM output signal. As shown in Fig. 1, each branch implements I-Q modulation by adding amplitude-modulated waves with a relative phase controlled by a phase bias. The complete module has 4 high-speed data inputs and 6 bias voltages. For PM-QPSK modulation, all 4 inner MZMs are biased to null, the X and Y phases are biased to $\pi/2$, and four binary data inputs are switched to $\pm V_\pi$, yielding a modulation loss of 3.0 dB. For cubic 8-SVM [7], inner MZMs XI, XQ, and YQ are biased to null, the MZM for YI is biased to max power, and the X and Y phases are biased to $\pi/2$ and 0, respectively. With quaternary data signals for XI, XQ and a binary data signal for YQ, the modulation loss is 5.6 dB.

Fig. 2 plots the complex amplitudes from the X and Y branches for the non-rectilinear Phi constellation, and lists the required bias and drive conditions. Setting both X and Y phases to $\pi/3$ enables higher output power from each polarization branch than is possible with a conventional phase of $\pi/2$, thus providing lower modulation loss. Inner MZMs XI, XQ, and YI are biased to null, YQ MZM is biased to max power, and binary data drives of $\pm V_\pi$ are input to XI, XQ, and YI. No data input is needed for YQ. The Phi constellation, shown in Fig. 3, has a modulation loss of

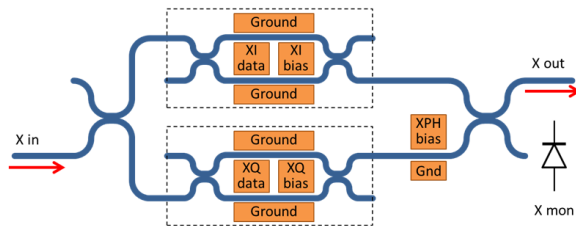


Fig. 1. X-polarization branch of the integrated PM-QPSK module. Each branch is a cascaded MZM with 3 biases and 2 high-speed data inputs.

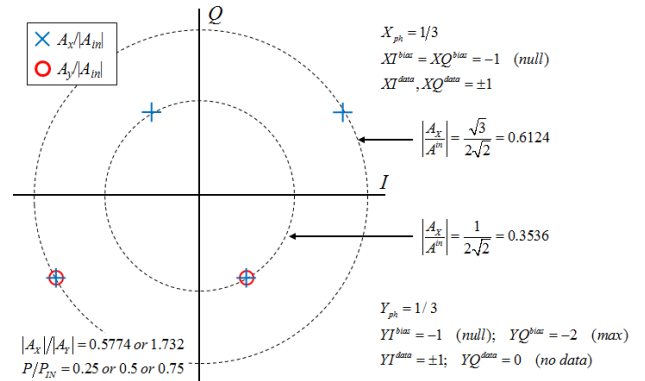


Fig. 2. Values of A_X/A_m and A_Y/A_m that are used for the Phi constellation, with bias and drive conditions.

just 3.0 dB, which is 2.6 dB better than the cubic scheme. Moreover, the electrical modulator driver circuits needed for binary data signals can be less expensive and more power-efficient than the drivers for quaternary signals, and binary drive signals are much less degraded by ISI than quaternary ones. Finally, we note that the MZM bias points are simple ones that are compatible with existing technology for automatic bias control, and that all data drives have the same amplitude, simplifying practical implementation.

3. Error Rates – Calculation of the theoretical symbol error rate (SER) is less straightforward for the Phi constellation than it is for rectilinear constellations, since the points are not equally spaced and the decision zones surrounding each constellation point do not take rectangular shapes. Still, an approximate comparison of the relative loss budgets can be obtained from the distances between nearest-neighbor symbol points in Stokes space [5]. The nearest neighbor distance for the cubic constellation is $|\Delta S| = 0.3179P_{in}$, where P_{in} represents the total optical power input to the PM-QPSK module. For the Phi constellation, we find $|\Delta S| = 0.5000 P_{in}$, implying an improvement of 2.0 dB in the total loss budget.

Fig. 4 plots the experimentally observed SER for the cubic constellation and for the Phi constellation, using a Stokes vector receiver (SVR) and a short fiber link including a variable attenuator, as described in [4, 7]. The arrows at the bottom of the plot represent the highest channel loss for which error-free transmission of 10^6 symbols was observed. The loss budget improvement of the Phi constellation over the cubic one, measured at $SER = 3 \times 10^{-4}$, is 2.5 dB for 7.5 Gb/s, 3.0 dB for 15 Gb/s, and 5.2 dB for 30 Gb/s. These improvements are larger than the value predicted from the nearest-neighbor distance, showing that the Phi constellation has a lower implementation penalty than cubic 8-SVM, thanks to its very simple bias points and data signals. In particular, severe ISI at 30 Gb/s leads to a shallow SER slope and prevents error-free operation in the cubic constellation, while the greatly reduced ISI in the Phi constellation permits error-free operation with 7.3 dB of link loss.

4. Conclusion & Acknowledgement - We have introduced a new constellation for 8-SVM signaling that we call the Phi constellation. Analysis of the Phi constellation predicts that it offers lower modulation loss and better link loss budget than a cubic constellation, while using simpler binary-only drive signals. Lab experiments confirm the predictions, and show that implementation penalties such as ISI are also reduced, leading to a 5.2 dB increase in the link loss budget at 30 Gb/s.

This work was supported in part by the USA National Science Foundation (NSF) under awards 1609389 and 1910140.

5. References

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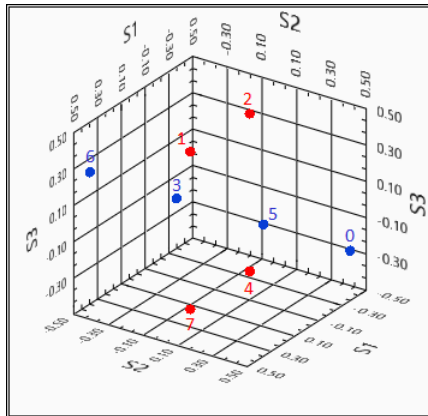


Fig. 3. Phi constellation in Stokes space. S_i values are normalized to P_{in} .

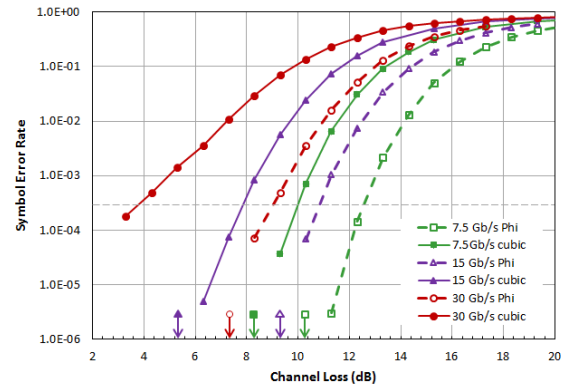


Fig. 4. SER vs. channel loss for 8-SVM transmission, comparing the phi constellation to a cubic constellation.