Digital Lightpath Label Transcoding for Dual-Polarization QPSK Systems

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Abstract: We introduce digital lightpath labeling for DP-QPSK transmission, using novel binary encoding to embed a polarization-shift-keyed subchannel. An integrated inline polarimeter powers a compact label receiver with robust tolerance to polarization rotation in a 40Gb/s demonstration.

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1. Introduction

Optical networks must simultaneously grow faster, more efficient, and more flexible. It is now widely accepted that long-haul fiber transmission at 100Gb/s will utilize dual-polarization quadrature phase-shift keying (DP-QPSK). At the same time, wavelength routing is an essential feature for network efficiency and flexibility[1-3], so lightpath verification methods are being developed to support such routing[4-6]. Digital labeling techniques attain excellent performance with minimal added hardware, but so far have been reported only for OOK[5] and DPSK[6] modulation at 10 Gb/s data rate.

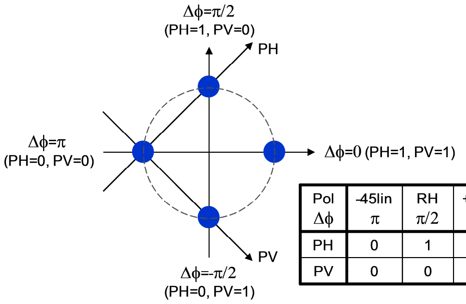
In this paper, we introduce a new digital encoding optimized for systems using DP-QPSK transmission. To enable label receivers that are simpler than DP-QPSK receivers, the new method is designed to encode a low-speed label subchannel in polarization-shift-keying (PolSK) format, by choosing appropriate codewords from the high-speed DP-QPSK symbols. Correct operation is verified in the lab by measuring label error rates in a system with 40Gb/s payload data rate. A receiver design that accommodates rapid polarization rotation during transmission is also demonstrated.

2. Digital Label Transcoding for DP-QPSK

Digital label encoding takes place in the source transmitter electronics, before modulation onto the optical carrier. LightLabel for OOK format (LL-OOK), based on Complementary Constant-Weight Coding with Code-Division Multiple Access (CCWC/CDMA), provides a serial binary output, with the label message carried in its low frequency components[5]. There is no interference between label information and payload, and labels from multiple λs can be read simultaneously with a single photodetector (PD), without needing to decode the payload bit stream. Thanks to the high sensitivity achieved with CCWC/CDMA coding, LL-OOK messages can be received by low-speed (~10 MHz) receivers attached to low-ratio tap couplers.

For DP-QPSK, a more sophisticated solution is needed. If the label were encoded in the same DP-QPSK format as the payload, the label receiver would become unacceptably complex and expensive. Instead, we have developed a transcoding process in which the payload stream is modulated in DP-QPSK format, but the embedded label subchannel appears as a low-rate PolSK signal, allowing the use of a simple PD behind a polarizer as the basic label receiver. At the transmitter, a standard DP-QPSK modulator is used; the only change is in the coding of the four binary tributaries.

To understand the transcoding process, note that DP-QPSK modulation, usually described as four phase states in each of two independent polarizations, can alternatively be seen as four polarization states with four phase states of



Pol Δφ	-45lin π	RH π/2	+45lin 0	LH −π/2
PH	0	1	1	0
PV	0	0	1	1

Fig. 1. Phasor diagram and state table for polarization states of a DP-QPSK signal.

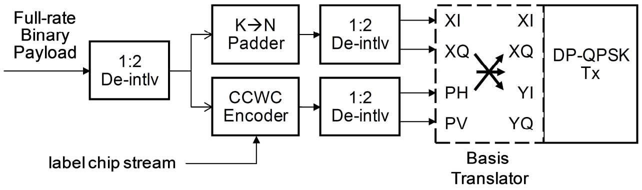


Fig. 2. Block diagram of transcoder to embed PolSK lightpath label within a DP-QPSK data stream.

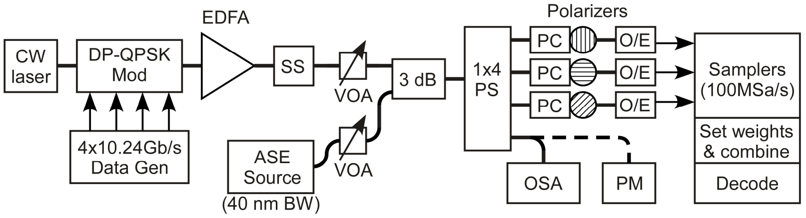


Fig. 3. Experimental setup for the lab demo. PC is a manual polarization controller, PS is a power splitter, SS is a computer-controlled synchronous polarization scrambler, and PM is a polarimeter.

the X-polarized component. The two descriptions are fully equivalent. The polarization states may be conveniently be identified as +45° linear, -45° linear, left-hand circular, and right-hand circular, representing relative phases of 0, π, $+\pi/2$, and $-\pi/2$ as shown in the phasor diagram of Fig. 1.

With this polarization-based description of the DP-QPSK signal in mind, it is clear that a simple polarized receiver, comprising a PD behind a polarizer set to +45° linear, will discriminate among the polarization states – its normalized output will be 2 when $\Delta\phi=0$, 0 when $\Delta\phi=\pi$, and 1 otherwise. Referring to the table in Fig. 1, the polarized receiver simply sums the '1' bits in the two polarization tributaries PH and PV. Thus, the label subchannel can be encoded as a low rate PolSK signal by controlling the total number of '1' bits in PH and PV within each codeword. A block diagram of such an encoder, using the CCWC/CDMA coding developed for LL-OOK, is shown in Fig. 2. The full-rate data stream is deinterleaved into X-phase and polarization substreams, then the polarization substream is encoded, while the X-phase stream is padded to accommodate the overhead (~1-2%) used in the CCWC/CDMA coding. After a second deinterleave step, the PH and PV polarization tributaries carry the PolSK label message. Finally, a basis translator is applied to convert the tributary set {XI, XQ, PH, PV} into the tributary set {XI, XQ, YI, YQ} expected by the standard DP-QPSK transmitter.

The receiver described above, with a single polarizer and photodiode, is susceptible to rotation of the state of polarization (SOP) during transmission; we have measured this effect and its mitigation experimentally.

3. Experimental Demonstration

The experimental setup is shown in Fig. 3. Block length and other CCWC/CDMA parameters were the same as in [5]. The uncoded payload rate was 40.00 Gb/s, the encoded rate was 40.96 Gb/s, the LightLabel chip rate was 20 Mchips/s and the frame rate was 100 kframes/s for each λ. An integrated 100G DP-QPSK modulator similar to that described in the OIF standard[7] was used to generate the signal and a flattened ASE source provided broadband noise from 1530-1564 nm. A polarimeter and synchronous scrambler were included in the transmission path to study the effect of SOP rotation on receiver performance.

Fig. 4 shows the measured label frame error rate (FER), as a function of optical signal-to-noise ratio (OSNR), for the simple receiver described above. When the SOP is stable and well-aligned with the axis of the polarized receiver, the OSNR sensitivity, defined at FER=3x10^{-4}, is 2.3 dB and there is no sign of an error floor. However, when the SOP is continuously scrambled at a rate of ~850 °/s on the Poincare sphere, the error rate has a conspicuous floor at FER>10^{-2}, showing the degraded sensitivity of the simple receiver when the received signal polarization is arbitrarily misaligned. In fact, theory shows that the received label signal should be proportional to the cosine of the angle of rotation (in Poincare space) away from perfect alignment with the receiver. Thus, for SOP points along a great circle on the Poincare sphere, the simple receiver will recover no label message at all.

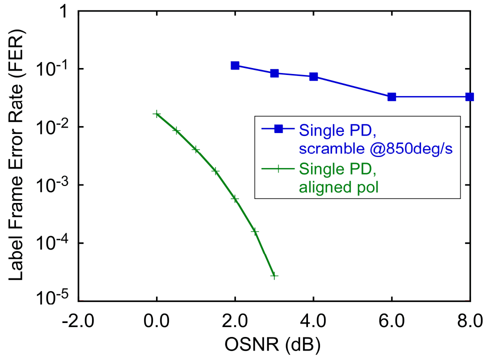


Fig. 4. Label error rate vs. OSNR for single-branch polarized receiver.

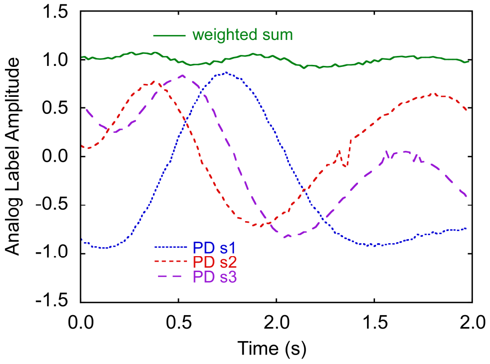


Fig. 5. Label frame amplitude vs. time for 3-branch Rx under polarization scrambling at 850 °/s.

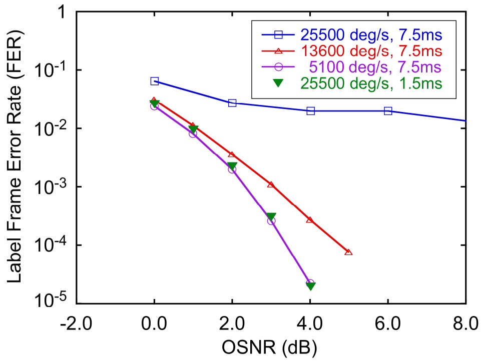


Fig. 6. Label error rate vs OSNR, for 3-branch Rx, with various scrambling rates and adaptation times.

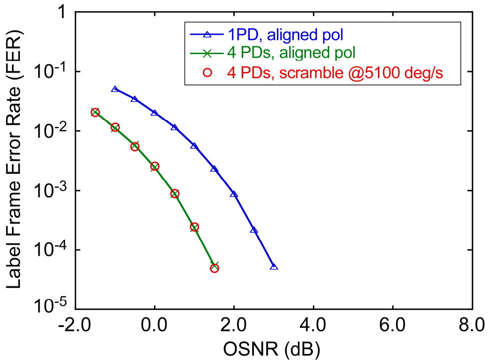


Fig. 7. Label error rate vs OSNR, using a 4-branch in-line polarimeter as the Rx front end.

Rather than attempt to track the incoming SOP, we have studied polarization-diverse receivers that provide multiple photodiodes, each with its own polarizer aligned to a separate SOP. For experimental flexibility, we used a discrete power splitter with three individual polarization controllers and polarizers, as shown in Fig. 3. The three receiver branches were aligned along the s1, s2, and s3 directions in Stokes space. We have also tested an integrated in-line polarimeter[8] head as a receiver front end. This fiber grating device advantageously combines 4 optical power taps and 4 polarizer/detectors in a stable, compact unit. For either front end, a weighted linear combination of the branches was used, with branch weights derived from each detector's frame amplitude.

Fig. 5 shows the time evolution of the analog frame amplitude from each of the three branches of a polarization-diverse receiver, at a scrambling rate of 425 °/s. For any single branch, the amplitude approaches zero at some instants, leading to the error floor noted in Fig. 4. However, by weighting the branches according to their instantaneous frame amplitude, the combined signal is nearly constant, which allows error-free reading of the PolSK label at all time instants (i.e., over all SOP rotations).

The measured FER for the 3-branch receiver is plotted for several different scrambling rates in Fig. 6. The maximum scrambling rate that can be tolerated depends on the adaptation rate of the branch weights in the receiver software. Thus, a receiver with an adaptation interval of 7.5 ms suffers significant penalties as the scrambling rate reaches and exceeds 13,600 °/s, while a receiver with an adaptation interval of 1.5 ms is still unaffected at a scrambling rate of 25,500 °/s. In principle, very short adaptation times could degrade performance by increasing uncertainty in the branch weights, but our studies show no such effect for adaptation times as small as 0.2 ms.

Comparison of Fig. 6 to the aligned case of Fig. 4 reveals a small residual OSNR penalty induced by scrambling, about 0.7 dB. As shown in Fig. 7, significantly better OSNR sensitivity is achieved using the integrated in-line polarimeter (IIP)[8], based on tilted fiber Bragg gratings. The IIP has four branches span the Poincare sphere, guaranteeing that for any SOP rotation, there exists a linear combination of branches which will reduce the effect of ASE noise. The effect is analogous to the use of balanced detectors in phase-shift-keyed systems. The OSNR sensitivity of the integrated 4-branch receiver is 0.9 dB, about 1.4 dB better than the simple receiver of Fig. 4 and about 1.5 dB better than single-branch reception with any one detector of the IIP. The 4-branch receiver attains the same sensitivity whether the polarization is scrambled or static, confirming the robustness of the system.

4. Conclusion

We have reported a new transcoding method that produces PolSK labels embedded within a DP-QPSK data stream, and used it in the first demonstration of digital lightpath labeling for 40Gb/s systems. A polarization-diverse Rx based on an integrated inline polarimeter successfully recovered the labels over all states of polarization rotation and scrambling. We wish to thank C. Clarke and S. Morasca of Oclaro, Inc. for providing the integrated modulator, and to acknowledge valuable contributions by L.E. Nelson, S.L. Woodward, and P. Magill of AT&T Labs – Research.

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