Cycle Slip Mitigation in POLMUX-QPSK Modulation

H. Zhang, Y. Cai, D. G. Foursa, and A. N. Pilipetskii
Tyco Electronics Subsea Communications, 250 Industrial Way West, Eatontown, NJ 07724
Phone: (732) 578 7449, fax: (732) 578 7302, e-mail: hzhang@subcom.com

Abstract: We demonstrate a pilot-symbol assisted joint polarization carrier phase estimation technique that detects cycle slip and avoid error propagation. Coherent detection without differential coding is feasible when the cycle slip probability is less than 10^{-3}.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications

1. Introduction

Coherent POLMUX-QPSK modulation is studied for both 40 Gb/s and 100 Gb/s long-haul optical transmission systems. In these systems, coherent detection using absolute phase will easily allow the use of soft decision FEC with high coding gain and thus will provide significant advantage over differential coding (DC). However, differential logical detection is typically used to avoid error propagation when cycle slips (CS) of carrier phase estimate (CPE) occur. Without differential coding, the CS probability must be maintained less than 10^{-18} for any coherent transmission system [1].

Recently, pilot-assisted decision-aided maximum likelihood phase estimate was proposed to prevent error propagation without differential coding [2]. The QPSK sensitivity was improved by 0.7 dB at 2,500 km distance in the simulation model. However this scheme does not correct the carrier phase error due to cycle slips. Therefore, the performance improvement can not be maintained when the cycle slip probability is high as is the case in long-haul systems where nonlinearities are typically higher. Furthermore, this decision directed phase estimate will have long feedback delay because the coherent receiver processes the data in parallel streams at the lower rate than the symbol rate. So the performance is considerably worse than the M-th power phase estimate in nonlinear systems. In this paper, we propose a pilot-assisted joint polarization M-th power phase estimation technique. We demonstrated that it allows us to use absolute carrier phase estimate instead of differential coding in a 7,200 km transmission experiment. With regular M-th power phase estimate, the QPSK receiver without differential coding failed at distances greater than 4,200 km due to cycle slips caused by nonlinear phase wandering [4,5]. The cycle slip probability was estimated at about $1.5\text{x}10^{-3}$ with a regular M-th power scheme after 7,200 km in this dispersion compensated system.

2. Pilot-Symbol Assisted Joint Polarization Phase Estimate

In our proposed scheme, there are P-length pilot symbols with known data information such as headers for FEC frames that are periodically inserted after D-length data transmission in both orthogonal polarization tributaries. The transmission overhead can be represented as P/(P+D). In out experiment, we selected a 2% overhead to limit OSNR penalty to 0.1 dB.

In the coherent receiver, the input data are demultiplexed and processed in multiple parallel processing units. The carrier phase of the P-length pilot symbols are estimated in the beginning of each processing unit. If the pilot symbols x(n),x(n+1),…x(n+P-1) and y(n),y(n+1),…y(n+P-1) have the known data information as d, then the phases of pilot symbols are estimated by

$$\begin{aligned} \phi_x(n),\ldots,\phi_x(n+P-1) &= \arg\left\{\sum_{k=0}^{P-1} d^* x(n+k)\right\} \\ \phi_y(n),\ldots,\phi_y(n+P-1) &= \arg\left\{\sum_{k=0}^{P-1} d^* y(n+k)\right\} \end{aligned} \tag{1}$$

Next, the forward estimated carrier phase of the D-length data symbols x(n) and y(n) in both polarizations are corrected with a feedback (FB) phase of the preceding symbols as

$$\phi_x(n)=\phi_x(n-1)+\frac{\mu}{4}\arg\left\{\sum_{k=0}^{N}x^4(n+k)e^{-i4\phi_x(n-1)}+\mathbf{C}\sum_{k=0}^{N}y^4(n+k)e^{-i4\phi_y(n-1)}\right\}$$

$$\phi_y(n)=\phi_y(n-1)+\frac{\mu}{4}\arg\left\{\sum_{k=0}^{N}y^4(n+k)e^{-i4\phi_y(n-1)}+\mathbf{C}\sum_{k=0}^{N}x^4(n+k)e^{-i4\phi_x(n-1)}\right\} \quad (2)$$

This FB method is similar to [3] and is utilized to explore the partial coupling of the phase change between two polarizations though the absolute carrier phase between the two polarizations may be different. In this paper, Weiner filter coefficient μ is used to optimize the phase estimator. N is the window size of forward symbols. When N=0, this method is the same as zero-lag Weiner filter [1]. The coupling coefficient $C\in(0,1)$ is chosen as 0.6 in our experiment.

The estimated carrier phase of pilot symbol is unambiguous because there is no 4th power calculation. Therefore it is used as a reference to compare with the estimated phase of the preceding data symbol as shown in Fig. 1. If the phase difference between pilot symbols and the preceding data symbol is larger than a predetermined threshold, e.g., π/3 radian, then a cycle slip might happen during the period of pilot symbols. When a cycle slip occurs, the estimated phase moves into the wrong quadrant with a least a π/2 offset in the case of QPSK modulation.

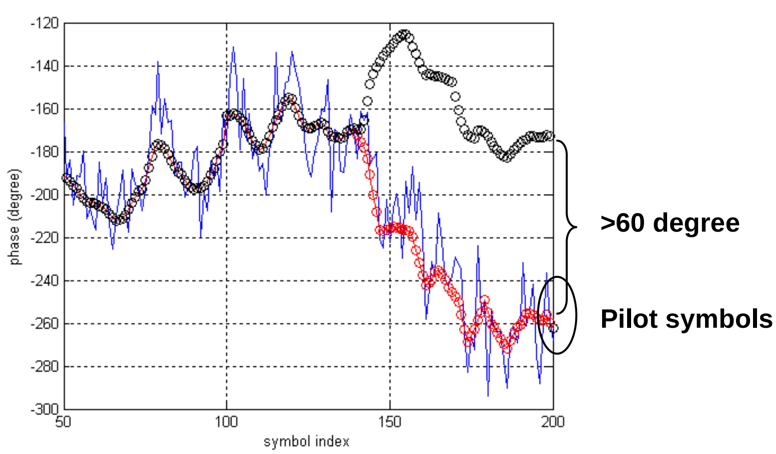

Fig. 1: Blue line is the carrier phase after removing data modulation. Black line is the forward carrier phase estimate and the red line is the backward carrier phase estimate. Cycle slip is detected by comparing the forward phase estimate with the phase of pilot symbols.

After a cycle slip is detected, the carrier phase of the D-length data symbols within the period of pilot symbols can be partially recovered by linear interpolation. This method is simple but may have large error if the phase fluctuation is large. We propose to estimate carrier phase of data symbol backward from the pilot symbol. The backward phase estimate is implemented as the following

$$\phi_x(n)=\phi_x(n+1)+\frac{\mu}{4}\arg\left\{\sum_{k=0}^{N}x^4(n-k)e^{-i4\phi_x(n+1)}+\mathbf{C}\sum_{k=0}^{N}y^4(n-k)e^{-i4\phi_y(n+1)}\right\}$$

$$\phi_y(n)=\phi_y(n+1)+\frac{\mu}{4}\arg\left\{\sum_{k=0}^{N}y^4(n-k)e^{-i4\phi_y(n+1)}+\mathbf{C}\sum_{k=0}^{N}x^4(n-k)e^{-i4\phi_x(n+1)}\right\} \quad (3)$$

Cycle slip is estimated to happen at the data symbol which has minimum difference between forward and backward estimated phase. The carrier phase after this data symbol is replaced with backward estimated carrier phase as illustrated by the red line in Fig. 1.

3. Experimental Performance

Pilot-assisted joint polarization carrier phase estimation method was tested using 40 Gb/s RZ-QPSK POLMUX with 33 GHz channel spacing and a dispersion compensated transmission line that exhibited fast phase wandering [4]. Two orthogonal polarization tributaries were driven at a symbol rate of 11.5 Gbaud with a quarter word shift in the 2^{23}-1 PRBS pattern and combined with a polarization beam combiner. The circulating loop testbed consisted of six 100-km amplifier spans. Each span had 50 km positive dispersion large effective area fiber ~ 135 μm^2 and 50 km pure silica core fiber. The accumulated dispersion was compensated by -2300 ps/nm DCF module in the dual-stage EDFAs. The digital coherent receiver is based on data acquisition with a real-time oscilloscope and subsequent off-line data processing. The carrier phase was estimated by pilot-assisted joint polarization CPE. Figure 2 shows the optimal performance achieved by using absolute carrier phase without differential coding and with differential coding for the transmission distance between 4,800 km and 7,200 km. At optimal power, coherent QPSK receiver without differential coding outperforms DC-QPSK by ~0.3 dB. If the carrier phase was estimated by regular M-th power CPE, then coherent QPSK receiver without differential coding failed at the distance greater than 4,200 km [4, 5]. This test shows that the proposed carrier phase estimation technique will enables coherent detection with absolute carrier phase instead of differential coding in most of the legacy systems.

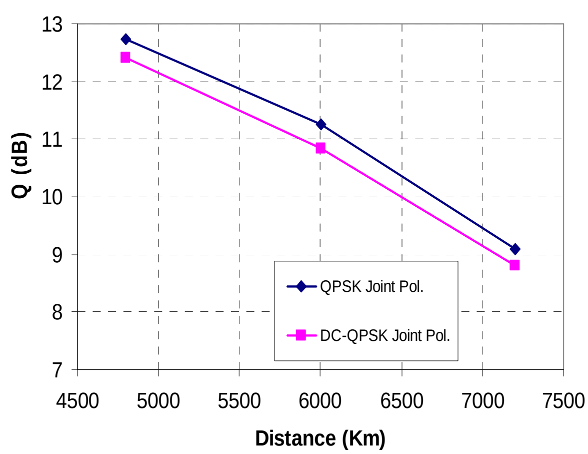

Fig. 2: optimal Q-factor for coherent QPSK and DC-QPSK in different system distance

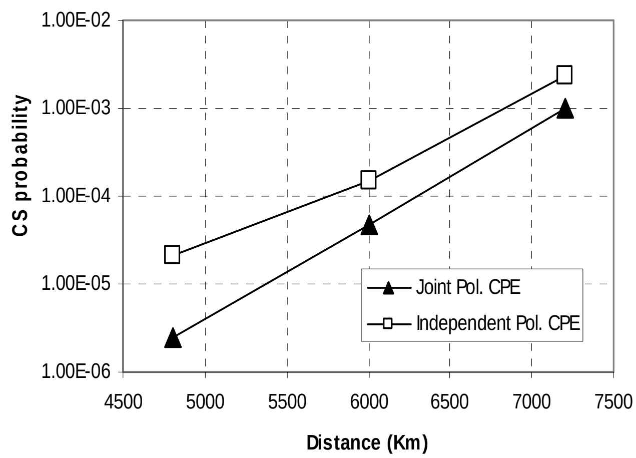

Fig. 3: Estimated cycle slip probability vs. different system distance w/o joint polarization

We also estimate the probability of cycle slip with and without the use of joint polarization CPE. The cycle slip event is decided when the phase difference between pilot symbols and the preceding data symbol is larger than $\pi/3$ radian. Figure 3 shows that joint polarization CPE can significantly reduce the cycle slip probability. It also shows that the cycle slip probability increases with the transmission distance and is about 10^{-3} after 7,200 km transmission. This experiment shows that pilot-symbol assisted joint polarization phase estimate enables coherent QPSK without differential coding and maintains performance improvement when the cycle slip probability is less than 10^{-3}.

Conclusions

We have proposed and demonstrated a pilot-symbol assisted joint polarization carrier phase estimation technique that enables coherent QPSK without differential coding in long-haul dispersion compensated system. The acceptable cycle slip probability to avoid differential coding is increased from 10^{-18} to 10^{-3}.

References

1 M.G. Taylor, J. Lightwave Technol. **27**, 901 (2009).
2 S. Zhang et al., IEEE Photonics Tech. Letter, **22**, 380 (2010)
3 M. Kuschnerov et al., ECOC 2008, Mo.4.D.2
4 Y. Cai et al., OFC 2010, OTuL2
5 D.G. Foursa et al., OFC 2010, OTuD2