A Novel Architecture of Flexible-Bit-Rate Transponder via Polarization Manipulation

Shaoliang Zhang[1], Fatih Yaman[1], Eduardo Mateo[2], Yoshihisa Inada[2], Takanori Inoue[2], Takaaki Ogata[2], Yasuhiro Aoki[2]

[1]NEC Laboratories America, Inc., 4 Independence Way, Princeton, NJ 08540, USA
[2]Submarine Network Division, NEC Corporation, 34-6, Shiba 5-chome, Minato-ku, Tokyo, 108-0014, Japan
Email: szhang@nec-labs.com

Abstract: To make single dual-polarization (DP) quadrature phase-shifted keying (QPSK) transponder to carry different bit rate, a binary bit encoder is proposed in this paper to manipulate the signal polarization multiplexing schemes into polarization-multiplexed (PolMux), Polarization-Switched (PolSw), and Polarization-Alternated (PolAl), such that the transmission bit rate could be adjusted depending on the system requirements and conditions. The performance of these modulation formats has been evaluated experimentally at 32 Gbaud in a dispersion-managed fiber (DMF) link. Compared with the ~4,500 km transmission distance using PolMux QPSK signal at 0.5 dB system margin, the transmission reach of PolSw and PolAl QPSK has increased to ~6,400 km and ~8,500 km, respectively, thanks to the lower bit rate of PolSw QPSK (96 Gb/s) and PolAl QPSK (64 Gb/s), and the superior characteristics of PolSw and PolAl schemes.

1 INTRODUCTION

While pursuing for the high-capacity transmission over single fiber for 400G and 1 Tb/s per wavelength, optical communication is opening up to become more flexible for meeting the diversity of Internet services. The paradigm of elastic optical networking (EON) has started to attractive more and more attention for establishing a flexible and adaptive network such that maximizing the spectrum efficiency (SE) [1]. The key players in this new paradigm will be the adaptive transponders, flexible grid and intelligent client nodes [1]. Meanwhile, the International Telecommunication Union (ITU) has already established 12.5GHz grid for scaling up the spectrum allocation from multiples of 12.5GHz bandwidth depending on the application, thus justifying the standard for a flexible grid for the future network service.

So far the submarine networks are still using the ITU 50GHz channel grid for 40G/100G transmission. In view of the research development of EON in terrestrial networks and the capability of coherent transceiver, flexible transponders are also important for delivering different data rate and achieving different transmission reach in submarine point-to-point links. For example, the 100G and beyond upgrade over legacy dispersion-managed fiber (DMF) would be very difficult to be done by using quadrature phase-shifted keying (QPSK) signals. In a flexible transponder, the software-defined optics (SDO) is the key enabler to adjust the signal baudrate and/or modulation formats depending on the specific upgrade link to achieve error-free transmission. As a result, the existing undersea cables would be maximally utilized with the help of this new EON paradigm.

To have a proof-of-concept demonstration of SDO, a binary bit encoder is proposed to be embedded into single dual-polarization (DP) QPSK transmitter so as to generate QPSK with different polarization multiplexing schemes: polarization-

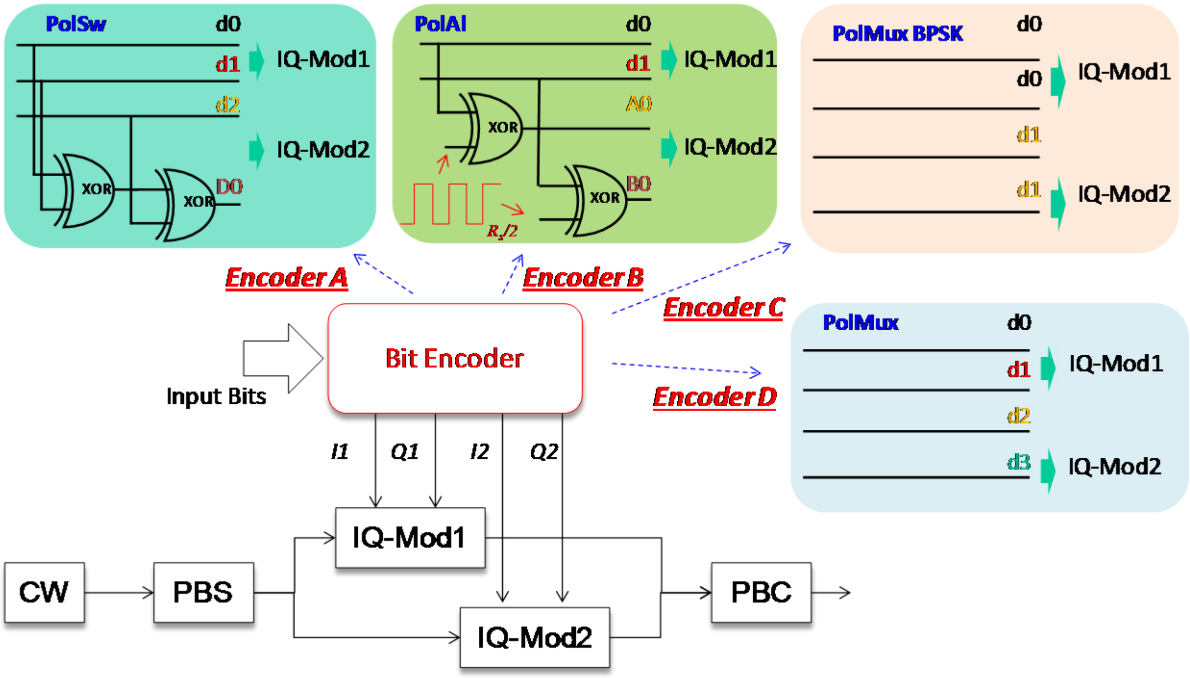

Figure 1 : The architecture of the proposed flexible transponder with four bit encoding modes for generating different polarization multiplexed signals.

multiplexed, polarization-switched, and polarization-alternation (PolAl). In this manner, the DP-QPSK transmitter can adjust its performance among PolMux, PolSw and PolAl QPSK formats in terms of receiver sensitivity, transmission performance, and bit rate. Therefore, the binary bit encoder equips the *single* DP-QPSK transmitter with the *flexibility* to change the modulation format according to the specific transmission link. The performance of the proposed flexible transponder architecture has been evaluated over a DMF testbed.

2 ARCHITECTURE OF FLEXIBLE TRANSPONDER

As depicted in Figure 1, the binary bit encoder would take in the input user bits and perform one encoding scheme (A, B, C or D) to generate different polarization-multiplexing signals. In encoder scheme D, PolMux QPSK carries independent QPSK symbols in both polarizations thus attaining a 4*B* bit rate in total, where *B* is defined as the binary bit rate. The PolSw signals utilize the polarization for carrying data, where the polarization state in which QPSK symbol locates is determined by polarization bits. To generate the PolSw signal, both the inputs to IQ-Mod1 and the inphase of IQ-Mod2 are the independent user bits, while the quadrature of IQ-Mod2 is the output of XOR operation among these three data (see encoder scheme A) [2]. With this bit encoding, only three independent user bits are used for generating each PolSw QPSK symbol, thus resulting in a bit rate of 3*B*.

In contrast to the PolSw QPSK signal, the polarization of PolAl signal alternates every symbol [3]. The advantage of PolAl is to mitigate the intra-channel fiber nonlinearity between neighboring symbols, thus improving transmission performance compared with single-polarization signal, in which all the signals are located in the same polarization state. Since the polarization alternation occurs every symbol, we propose to perform the XOR operation with a logical clock running at half of the symbol rate *B* which also alternates every bit, as shown in encoding scheme B. The outputs of XOR operation are fed into the IQ-Mod2 as the inphase and quadrature. Thus, the polarization of the modulated QPSK signal will change alternatively similar to the logical clock. In the PolAl scheme, two independent user data are only used for producing each PolAl symbol, thus delivering 2*B* bit rate.

In our design, the polarization scheme is able to be adjusted to PolMux, PolSw, or PolAl to equip the SDO capability for existing DP-QPSK transponders. The total bit rate is able to change from 2*B* till 4*B* with the proposed bit encoder scheme, thus enabling a low-cost design of SDO to existing DP-QPSK transponders. In addition to adjusting the polarization scheme of QPSK signals, this encoder is capable of generating the same data for both inphase and quadrature to have BPSK format (refer to encoding scheme C). The total bit rate is also 2*B* for PolMux BPSK format.

3 EXPERIMENTS

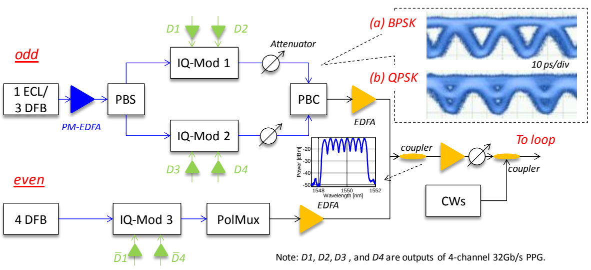

Figure 2 : Experimental setup for evaluating the flexible bit-rate transmitter.

3.1 Experimental Setup

A standard DP-QPSK transmitter shown in Figure 2 was used to offline emulate the SDO adaptation of the bit rate by adjusting the polarization multiplexing schemes through the proposed binary bit encoder as described in Section 2. Four different tributaries generated from the pseudo-random bit sequence (PRBS) of length 2^{15}-1 were uploaded into a PatternPro® pulse pattern generator (PPG) (Model 12072) which has four independent channels operating at 32Gb/s. The delay of these four tributaries was manually adjusted once in the PPG at the beginning of the experiments, and was found to be quite stable even though changing the data pattern to produce different polarization multiplexing schemes. The four binary outputs (*D*1, *D*2, *D*3 and *D*4) of the PPG drove the two IQ-modulators to generate either BPSK or QPSK signal depending on which bit encoder was applied. Insets (a) and (b) show the eyediagram of BPSK and QPSK signals. Different polarization multiplexing schemes, including PolMux, PolSw, and PolAl, can be obtained after combining these two polarizations with polarization beam combiner (PBC). To de-correlate the wavelength-division multiplexing (WDM) signals, the even channels were modulated by the outputs $\bar{D}1$ and $\bar{D}4$ of PPG. The 8 modulated 50GHz-spacing WDM signals were coupled with the other 80 continuous waves (CWs) before launching into the transmission link.

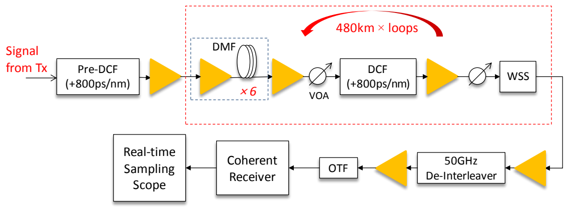

Figure 3 : Transmission link and receiver setup. OTF: optical tunable filter; VOA: variable optical attenuator.

Figure 2 describes the transmission link in this experiment. The launched signals first passed through a pre- dispersion-compensating fiber (DCF) module with + 800 ps/nm chromatic dispersion (CD) prior to circulating in the fiber loop. Each loop consisted of 6-span of 73 km dispersion-managed fibers (DMFs) and one span of DCF module with a nominal CD compensation of +800 ps/nm, leading to in total 480 km per loop. Each DMF span is composed of a 45 km positive dispersion (19 ps/nm/km) fiber with 0.2 dB/km loss and effective area of 93 μm^2, and another 28 km negative dispersion (-38 ps/nm/km) fiber with 0.245 dB/km loss and effective area of 24.5 μm^2. One wavelength selective switch (WSS) was inserted in the loop to ensure a flat gain over all channels. The loop configuration is an emulation of a typical legacy DMF-based submarine link.

At the receiver side, a 50GHz de-interleaver together with a 0.5 nm optical filter was used to select the center channel (1550.12 nm) for demodulation. The filtered channel was downconverted to electrical baseband by mixing with a local oscillator in a polarization-diversity optical hybrid followed by balanced photodetectors. The outputs were digitized by using two 2-channel real-time sampling scopes at 80 GS/s sampling rate and 30 GHz bandwidth.

Standard DSP algorithms were performed to recover PolMux QPSK and PolMux BPSK signals. Constrained constant-modulus algorithm (CCMA) was applied in PolSw QPSK format to effectively separate the two polarization states. Given the fact that the same receiver front-end is used for all PolMux, PolSw and PolAl signals, the sampling rate of the analog-to-digital converter (ADC) is at least 2*B*. It is straightforward that PolAl QPSK can still employ the same CCMA algorithm as in PolSw QPSK to separate two polarizations [4]. On the other hand, to utilize low-complexity regular constant-modulus algorithm (CMA), the PolAl QPSK signal can also be regarded as polarization-interleaved QPSK signals with 50% duty cycle in each polarization, resulting in a lower baud rate of *B*/2 QPSK signal which is digitized into four samples per symbol. Since there are 4 samples per symbol, the butterfly-like filter taps are updated every 4 samples instead of 2 samples in the regular CMA algorithm, which requires fewer modifications to the regular CMA and has less complexity.

3.2 Experimental Results

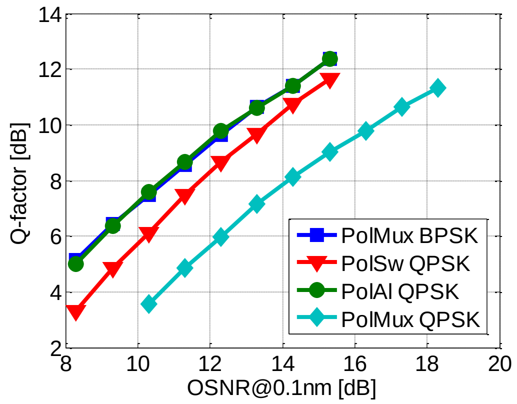

Figure 4 : Measured back-to-back Q-factor of different signals versus OSNR at 0.1 nm.

Figure 4 plots the back-to-back (BTB) Q-factor performance of all the 32 Gbaud signals as a function of optical signal-to-noise ratio (OSNR) at 0.1 nm resolution. As can be observed, PolAl QPSK has the similar performance as PolMux BPSK due to the fact that both modulation formats carry the same bit rate of 64 Gb/s data. This excellent performance of PolAl QPSK offers an effective approach to adjust the DP-QPSK transponder to improve system margin and extend transmission reach by only alternating the polarizations of signals. Although single-polarization QPSK is an another format with the same bit rate as PolAl QPSK, it is subjected to strong fiber nonlinearity in transmission because all the signals locate in the same polarization. Other than PolMux BPSK and PolAl QPSK formats, the flexible DP-QPSK transmitter is also able to produce PolMux and PolSw QPSK signals. The measured BTB results show that PolAl QPSK outperforms PolMux QPSK at 10 dB Q-factor by about 4 dB , which is 1 dB higher than the theoretical 3 dB difference.

This additional 1 dB penalty is attributed to the implementation penalty of PolMux QPSK format. The performance of PolSw QPSK signal is about 1 dB worse than PolAl QPSK. This difference accounts for higher bit rate and improved receiver sensitivity of PolSw QPSK signal: compared to 64 Gb/s PolAl QPSK, PolSw QPSK carries 96 Gb/s data, leading to $10\log_{10}(3/2) \approx 1.76\,\text{dB}$ receiver sensitivity penalty; on the other hand, PolSw QPSK is the most power efficient modulation format in a four dimensional constellation space, which has 0.97 dB sensitivity gain over PolMux BPSK format at the bit error rate (BER) of 10^{-3}[2]. This improvement of PolSw QPSK is experimentally demonstrated having ~0.6 dB over PolMux BPSK at the same bit rate [5]. Therefore, taking into account of both factors, PolSw QPSK is supposed to have ~0.8 dB penalty compared with PolMux BPSK signal at BER = 10^{-3} (Q-factor is around 9.8 dB), which is close to our measured ~1 dB penalty shown in Figure 4.

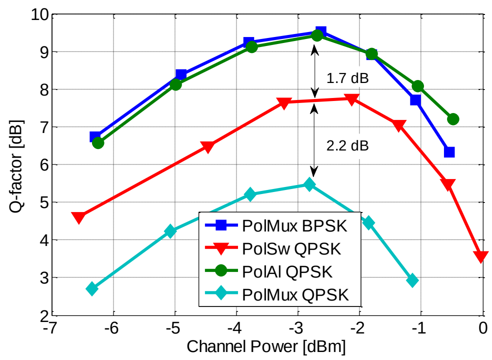

Figure 5: The measured Q-factor as a function of channel power at 12 loops.

The Q-factor is plotted against the launched channel power in Figure 5 at 12 loops for different polarization schemes. Interestingly, the optimal channel power for all the signals is quite similar, around -2.8 dBm, thereby suggesting that the optimal channel power is independent of modulation format and even transmission distance. Also, both PolAl QPSK and PolMux BPSK are found to have the same transmission performance in consistent with the BTB results. Therefore, PolAl polarization schemes can be applied into DP-QPSK transmitter to enhance its fiber nonlinearity tolerance and improve receiver sensitivity with the aid of the binary bit encoder proposed in Section 2. It is worth mentioning that PolAl QPSK even outperforms PolMux BPSK at high nonlinear regime due to its lower baud rate and polarization alternation features. At the optimal channel power, both the PolAl QPSK and PolMux BPSK signals have about 3.9 dB Q-factor improvement over PolMux QPSK because of the BTB receiver sensitivity. This improvement becomes even more at high channel power since BPSK and PolAl QPSK have better fiber nonlinearity tolerance than PolMux QPSK as well. The PolSw QPSK format seems to suffer from additional ~0.7 dB fiber nonlinearity penalty, thus reducing the measured Q-factor by ~1.7 dB compared to PolAl QPSK and PolMux BPSK formats.

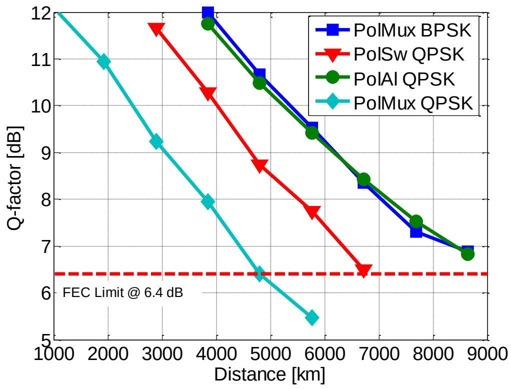

Figure 6: Q-factor versus transmission distance at channel power of ~ -2.8 dBm.

Figure 6 compares the transmission performance of all these four modulation formats at the optimal channel of -2.8 dBm in the DMF testbed. The baseline is the 128 Gb/s PolMux QPSK signal capable of reaching ~4,500 km with 0.5 dB system margin. The forward error correction

(FEC) limit is 6.4 dB with ~27% overhead according to the current commercial 100G DP-QPSK transponder. By adjusting the polarization schemes to PolSw and PolAl through the proposed binary bit encoder, PolSw QPSK and PolAl QPSK formats are able to transmit over ~6,400km and ~8,500 km, respectively, with the same system margin. This system improvement results from reducing the total transmission bit rate through the bit encoding as well as the polarization manipulation. For example, PolAl QPSK signal consistently has the same performance as PolMux BPSK, thus giving DP-QPSK transponder the flexibility to reach different transmission distance without much modification. The recovered constellations for each modulation format have been shown in Figure 7.

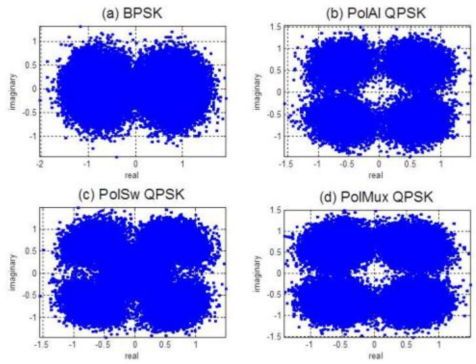

Figure 6: The recovered constellation of (a) PolMux BPSK after 16 loops; (b) PolAl QPSK after 16 loops; (c) PolSw QPSK after 12 loops; and (d) PolMux QPSK after 8 loops.

4 CONCLUSION

In this paper, a binary bit encoder is proposed to adjust the polarization schemes (PolMux, PolSw and PolAl) of output signals in single DP-QPSK transmitter, rendering in an SDO feature with variable bit rate of 4*B*, 3*B* and 2*B* data transmission. The proposed bit encoder is compatible with the existing DP-QPSK transponder to provide flexibility of transmission distance, bit rate, and system receiver sensitivity, thereby potentially making single DP-QPSK transponder to be used for upgrade over any link. Single offline DP-QPSK transmitter has been emulated for SDO features to produce 64Gb/s PolAl QPSK, 96 Gb/s PolSw QPSK and 128 Gb/s PolMux QPSK signals. Experimental results show that PolAl QPSK has the same transmission performance as PolMux BPSK format due to its polarization alternation feature. The 32 Gbaud PolMux QPSK is only able to transmit ~4,500 km over our DMF testbed. By manipulating its polarization into PolSw and PolAl, the maximum transmission reach with a half dB margin has been extended to ~6,400 km and ~8,500 km, respectively.

5 REFERENCES

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