Coherent UDWDM Transceivers Based on Adaptive Stokes Space Polarization Demultiplexing in Real-Time

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Abstract We experimentally demonstrate for the first-time a dual-polarization coherent UDWDM system supported by adaptive Stokes space polarization-demultiplexing implemented in real-time. Transceiver performance in terms of complexity and sensitivity is evaluated while the system supports optical power budget in excess of 38dB.

Introduction
Driven by proliferation of heterogeneous bandwidth consuming Internet services, the traffic demand over the access networks has been growing exponentially year after year. Future optical metro-access networks need new technology options to support high capacity, spectral efficiency and data-rate flexibility. Coherent detection is the next unavoidable step and provides an opportunity.
It is a reality that coherent brings higher cost and complexity to the optical network, specially to the user side. However, with today’s implementation of coherent transceivers in long-haul networks and recent advances in photonics integrated circuits, this cost can be reduced in near future\(^1\).\(^2\). Anyway, this transition period creates an opportunity for researchers to study new architectures and digital signal processing (DSP) to improve the performance and complexity of coherent transceivers, helping the standardization and industrial players to select the most efficient solutions in proper time. Despite of the increased cost and complexity, the migration to dual-polarization coherent transceivers must be consider, as it enables to double the spectral efficiency. These dual-polarization systems require an additional DSP subsystem for polarization demultiplexing. Despite of its widespread application, the well-known constant modulus algorithm (CMA) presents some important challenges, such as the probability of singularity and the dependence on the transmitted modulation format\(^3\).\(^4\). Recently, we have proposed an adaptive Stokes PolDemux technique has several advantages over CMA such as conversion speed, flexibility and avoidance of singularity\(^5\).\(^6\). However, the question related to real time implementation and complexity of algorithms in a real scenario is still open and under consideration. It has been shown for low baud rate signals as well as metro and access applications where the reach is in the short range, that dispersion is not an issue for these systems.
In this paper, we demonstrate a reconfigurable real-time DSP reception of a coherent ultra-dense wavelength division multiplexing (UDWDM) passive optical network (PON) system based on DP quadrature phase-shift keying (QPSK) signals, supported by a commercial field-programmable gate array (FPGA), four 1.25 Gsa/s analog-to-digital converters (ADCs) and DSP based on the adaptive Stokes PolDemux. A test bed based on 20 UDWDM channels with 625 Mbaud and 2.5 GHz channel spacing over 100 km of a standard single mode fiber (SSMF) is used for validation of PolDemux technique in real-time operation at the coherent receiver. We note that, the 625 Mbaud DP-QPSK signal was selected due to the limitation of the ADCs. The complexity of both PolDemux techniques based on CMA 1-tap and adaptive Stokes is investigated. The performance of this real-time system is validated for different optimization items such as sensitivity and nonlinearity. Bit error rate (BER) calculations regarding sensitivity and optical power budget is performed.

Experimental Setup and DSP Subsystems
In Fig. 1, we show the proposed experimental setup for validate and characterize the performance of UDWDM system based on Nyquist pulse shaped DP-QPSK signal a real time DSP based on adaptive Stokes PolDemux techniques. At the transmitter, four external cavity lasers (ECLs) (<100-kHz linewidth) with channel spacing of 2.5 GHz (wavelength \(\lambda\) is centered at \(\sim 1549\) nm) are injected into two IQ modulators (IQMs) driven by two 65 Gsa/s arbitrary waveform generator (AWG). The AWGs generate 625 Mbaud signals from a \(2^{12}-1\) pseudo random bit sequence (PRBS) with a RC shaping with 0.1 roll-off factor. The modulation format for
all four channels is the differential QPSK and providing 1.25 Gb/s and each neighbor channel is decorrelated. After modulation, the four channels are injected into an optical comb generator \(^1\) in order to replicate the four channels in 20 channels with a channel spacing of 2.5 GHz. The UDWDM signals were separated into two polarizations (12 symbols delayed for decorrelation purposes) using an optical delay line (ODL), and then multiplexed in polarization again by a polarization beam combiner, creating a dual polarization 2.5 Gb/s DP-QPSK. The optical spectrum of 20 channels is shown in Fig. 1 (b). The launch power per channel at the input of 100 km fiber was set by an erbium-doped fiber amplifier (EDFA) and a variable optical attenuator (VOA) prior to transmission link.

At the receiver side, an ECL (wavelength \(\lambda_1\) and 100 kHz linewidth) with 13 dBm optical power was used as local oscillator. UDWDM signals were detected using an integrated phase- and polarization-diversity coherent receiver followed by 1 GHz low-pass filters and four 8-bit 1.25 Gsa/s ADCs. Note that, only one output of differential outputs of TIAs was used (Fig.1c). The digitalized signal is sent to a Virtex-7 FPGA, where all post-detection 8-bit DSP in real-time is implemented (Fig.1 d and f). The DSP chain was comprised normalization, clock recovery, adaptive PolDemux, frequency and carrier phase recovery subsystems, as depicted in Fig. 1 (d). The BER is calculated in real-time by bit error counting, averaged between the two polarizations \(^7\). The clock of the DSP is set at 156.25 MHz, leading to a degree of parallelization (DOP) of 8 in order to process a sampling rate of 1.25 Gsa/s, i.e. two samples per symbol (SPS). In PolDemux part, both CMA 1-tap and the adaptive Stokes space were implemented for PolDemux algorithm and the performance of both of the techniques has been considered. By representing data in the Stokes space, the algorithm finds a best fitting plane, whose normal is then employed into the computation of the inverse polarization rotation matrix of the channel \(^4\). Fig 1. (f) reports the hardware complexity of both CMA and Stokes algorithms for DP-QPSK signals. The evaluation only considers the real multipliers, real adders and lookup tables (LUTs) as the most critical units of the designs. The value N corresponds to the number of parallel symbols given by \(T_{DSP}/T_{SYM}\), where \(T_{DSP}\) corresponds to the clock period of the DSP and \(T_{SYM}\) the symbol period of the signal. Thus, considering a DSP clock frequency of 156.25 MHz, N=8 is required to process a 1.25 Gb/s DP-QPSK signal, for instance. The column “Complexity” shows the total complexity of the algorithms based on an 8-bit real multiplier, considering 0.625, 1.25 and 2.5 Gb/s signals. The results should be analyzed as follows: for 2.5 Gb/s DP-QPSK (0.625 Gb/s signal), for instance, the 1-tap CMA algorithm has a DSP complexity similar to 144 real 8-bit multipliers. While the estimation flow of both algorithms can be designed with a DOP of one, i.e. only one of the 2N received parallel samples (when the signal is sampled with 2 samples per symbol) is
used in the estimation process, since the polarization rotation is generally slow, the feedforward branch of the algorithm requires a DOP of 2N to achieve the sampling high-speed throughput. Thus, as observed in the last column, the complexity between both algorithms (when parallelized hardware implementations are used) is similar when the symbol rate increases (N value grows), since the Stokes differs from the CMA only in the estimation flow of the Matrix coefficients. The complexity of the subsystem is given almost by the feedforward processing of the algorithm, which is equal for both algorithms.

**Experimental Results and Discussion**

In order to verify and assess the performance of both CMA 1-tap and proposed Stokes PolDemux, Fig. 2 shows the measured BER as a function of the receiver input power per multi-channel after transmission on 100 km SSMF. The launched optical power per channel in the input of fiber was set to -5 dBm. Results show an acceptable -42 dBm sensitivity considering a forward error correction (FEC)-compatible of BER = 3.8 × 10^-3. For received optical powers at this threshold, both algorithms present almost a similar performance for 20 UDWDM channels. Fig. 4 analyses the ODN power budget in 100 km SSMF of the center channel of 4 and 20 UDWDM channels. By changing the transmitted power at the input of fiber, the required received optical power for maintaining at the target BER of 3.8 × 10^-3 is determined. As shown in Fig. 4, maximum power budget of ~38 dB for 20 channels is obtained with -42 dBm sensitivity and the input power of -4 dBm. For 4 channels, maximum ODN power budget is 46 dB which obtained with 4 dBm transmitted power.

**Conclusions**

We have experimentally demonstrated a real time UDWDM DP-QPSK system based on both CMA 1-tap and the adaptive Stokes space PolDemux technique considering transmission over 100 km fiber. The comparisons between both adaptive equalizers were performed in terms of complexity and receiver sensitivity. In addition, the resiliency of the adaptive Stokes PolDemux technique was evaluated in terms of nonlinearity and an optical power budget of >38 dB was achieved dependent to number of channels.

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