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# Power Consumption of a Minimal-DSP Coherent Link with a Polarization Multiplexed Pilot-Tone

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***Abstract*** *We experimentally study the trade-off between performance and DSP power consumption. While minimal DSP allows transmission of 16QAM at 5 GBaud, the symbol rate can be increased if an extra equalizer is added, leading to energy savings in optical components.*

## Introduction

Coherent detection together with digital signal processing (DSP) has enabled high-speed data communication over long-haul distances, owing to the capability of DSP to compensate for linear transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD)[1]. For short-reach systems, however, the stringent limitations on size and power consumption have favored less complex directly modulated lasers together with direct detection. Nevertheless, as the bandwidth demand increases, coherent solutions become attractive also for shorter links. While a significant part of the power dissipation of coherent long-haul transceivers is due to the DSP needed for compensating CD and PMD[2], which can be reduced or omitted when moving to shorter links, there are parts of the DSP that are inherently necessary for the operation of the coherent receiver. If all-optical polarization alignment and local oscillator (LO) phase tracking mechanisms should be avoided, the main necessary DSP-functions are polarization demultiplexing and carrier recovery.

The complexity of both of these functions can be reduced by polarization multiplexing a pilot-tone with the signal. When the pilot-tone is used instead of an LO in the coherent receiver, this scheme is known as self-homodyne detection (SHD)[3] and it has been shown that SHD can be used to relax the need for carrier recovery[5]. It has also been shown that if such a signal is detected with a polarization diversity coherent receiver, a concept known as digital SHD (DSHD), the polarization alignment DSP can be simplified using a simple constant modulus algorithm (CMA)[4]. The only needed DSP is then a polarization demultiplexing 1-tap MIMO equalizer, digital self-homodyne mixing and a relatively slow phase offset compensation. We believe that this is the minimum DSP needed for coherent detection of phase-modulated signals.

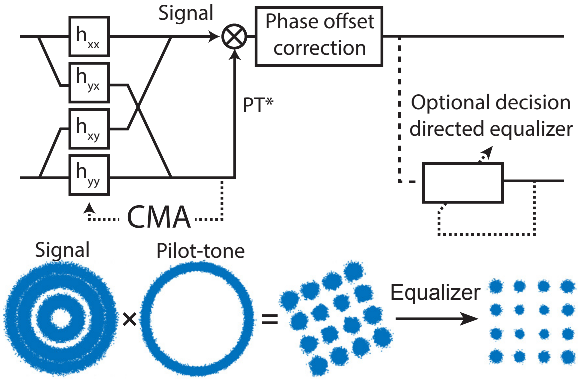

**Fig. 1:** The DSP analyzed in this work and the associated constellations.

In this paper, we experimentally demonstrate a minimal DSP DSHD receiver for 16QAM signals at 5 GBaud and estimate the power consumption of this from the power consumption of a 28 nm CMOS ASIC implementation. As the symbol rate is limited by the hardware bandwidth, we also investigate the number of taps needed in an additional equalizer to enable symbol-rates of 10, 15 and 20 GBaud and the extra power consumption associated with this.

## Minimal DSP For a Self-Homodyne signal

Compared to a standard coherent receiver, a polarization multiplexed pilot-tone simplifies two steps of the DSP chain. Firstly, the constant amplitude of the pilot-tone makes it possible to perform the polarization demultiplexing with a simple CMA algorithm even for higher order modulation formats such as 16QAM. Secondly, it replaces the computationally complex FFT-based carrier frequency offset (CFO) compensation with a simple sample-by-sample multiplication for the self-homodyne mixing.

The DSP analyzed in this work can be seen in Fig. 1. After resampling and orthonormalization, a 1-tap adaptive MIMO equalizer is used to sepa-

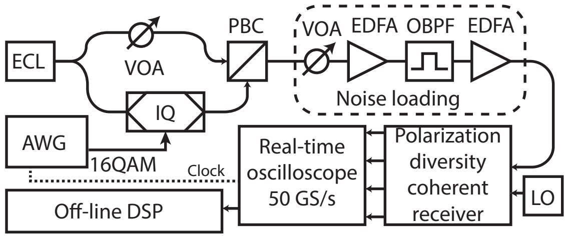

**Fig. 2:** The experimental setup.

rate the signal and pilot-tone. Unlike the standard CMA algorithm, the error signal is calculated from only one of the outputs, which will be forced to be the pilot-tone due to its constant amplitude. More details of this algorithm can be found in[4]. After the signal and pilot-tone has been separated, self-homodyne mixing is achieved by multiplying the signal with the conjugate of the pilot-tone.

After the self-homodyne mixing, the signal is nearly recovered except for a phase rotation due to small misalignments between the signal and pilot-tone. This phase rotation drifts slower than kHz-timescale[5] and can be tracked with low complexity DSP. The data can now be recovered from the signal, which is what we demonstrate in the next section. However, the symbol-rate will be limited by the bandwidth of the transmitter and receiver hardware. Since the CMA takes its error signal from the pilot-tone, it is incapable of detecting and compensating for such signal impairments. To investigate the impact of additional equalization on performance and power consumption, we used a separate decision-directed least mean squares (DD-LMS) adaptive equalizer after the self-homodyne mixing.

## Experiments

The experimental setup used can be seen in Fig. 2. A 100 kHz laser was used as a light source, and modulated with an IQ-modulator. The modulated light was then polarization multiplexed with the pilot-tone, consisting of the unmodulated carrier. The power of the pilot-tone was adjusted with a variable optical attenuator (VOA) to be equal to the average power of the signal. The 16QAM signal was generated at 60 GS/s with a 20 GHz bandwidth arbitrary waveform generator (AWG), and the symbol rate was adjusted to 5, 10, 15 and 20 GBaud by changing the number of samples per symbol. Rectangular pulses were used and no effort was made to pre-emphasize the pulses to account for the spectral response of the AWG.

To evaluate the performance of the DSP, we added ASE to the signal in a noise-loading stage. The signal was then detected with a standard polarization diversity coherent receiver and sampled at 50 GS/s with a 23 GHz bandwidth real time oscilloscope. The sampled data was then off-line processed, according to the previous section with only phase-offset compensation or with 4, 8 or 16 taps in the DD equalizer. The phase offset compensation was done by doing a DD blind-phase search (BPS) on 1000 samples, which was enough for the equalizer to properly converge. When no equalization was done to get a finer estimation of the phase offset a 1-tap version of the DD-equalizer was converged on 10000 samples, and the final tap value multiplied with the whole batch.

## Power Consumption Estimations

The DSP power consumption was based on the CMA-equalizer presented in[6], as the structure is similar. The standard CMA equalizer was synthesized with 6-bit signal and tap word-lengths, and power was estimated using data generated in the same simulation setup as in[6], with 128-way parallelization at 28 GBd and 16 samples per block for coefficient update calculation, and 4, 8, and 16 taps. This should be sufficient to track polarization rotation speed of more than 100 krad/s, which is unlikely to occur for the system considered in this work. The power consumption is dominated by dynamic power, which scales linearly with clock frequency and circuit complexity, and the equalizer power consumption thus scales linearly with symbol rate.

The polarization-demultiplexer is a single-tap non-downsampling CMA-equalizer, assuming linear power scaling with respect to number of taps and the fact that the equalizer in[6] downsamples 2 to 1 sample-per-symbol, power is estimated to be $P_{poldemux} = 2 \cdot P_{MIMO}/N_{taps}$. The DSHD polarization demultiplexer only performs error calculation and gradient estimation on one polarization and calculates the taps based on constraining the Jones matrix to be unitary and then mixes the output polarizations, while a standard MIMO equalizer performs error calculation and gradient estimation on both polarizations. In this work, we assume that the mixing operation is less power consuming, and thus linear scaling gives a conservative approximation. The 4-tap MIMO configuration was used for this estimation.

The DD equalizer is modelled to have a quarter of the power consumption as a 2×2 MIMO equalizer. CMA error calculation and DD error calculation is assumed to be similar, and minor contribu-

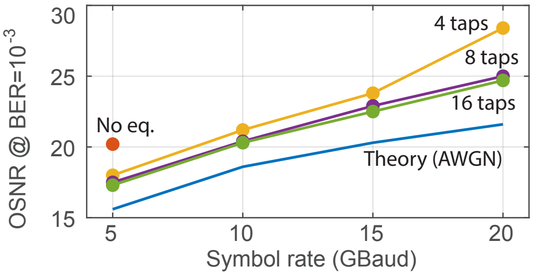

**Fig. 3:** Required OSNR for BER$=10^{-3}$.

tors in respect to other blocks, since only decision and subtraction is needed.

We note that these estimations do not capture signal-dependent effects on power consumption.

## Results and Discussion

In Fig. 3 the required OSNR for a BER of $10^{-3}$ is plotted versus the symbol rate for different equalizer configurations. Achieving BERs below $10^{-3}$ with no equalization was only possible at 5 GBaud, and performance also becomes sensitive to the sampling instant. Using 8 taps in the equalizer gives only a small penalty compared to 16 taps, while using only 4 taps degrades the performance. Since the energy consumption is modeled as linearly dependent on symbol rate, the energy per bit values are the same for all symbol rates, found to be 3.4 pJ/bit for the polarization demultiplexing and 1.7 pJ/bit, 3.3 pJ/bit, 5.8 pJ/bit for the 4, 8 and 16 tap equalizer respectively. We also verified that quantization of the signal and taps to 6 bit resolution gave under 1 dB penalty at BER$= 10^{-3}$ with respect to plotted values.

To compare the different symbol-rates cases in terms of energy consumption per bit, we picked the least complex DSP-configurations that achieved a BER of below $10^{-3}$ at an OSNR of 25 dB. For 5 GBaud this was the minimum DSP case with no additional equalization and for 10, 15 and 20 GBaud extra equalization with 4, 8 and 16 taps respectively was needed. Bar graphs of the energy per bit values can be seen in Fig, 4. We also compared the DSP power consumption values with the power consumption of the most power consuming parts of a coherent transceiver, based on the values used by Pillai et al.[2]. The values used were 2.5 W for a laser, 3.5 W for an IQ-modulator driver and 37.5 pJ/bit for 4 ADCs.

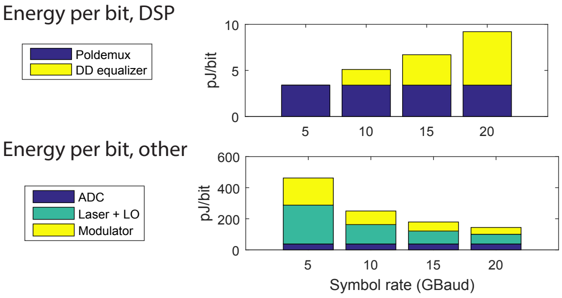

**Fig. 4:** Energy per bit values for DSP and other significant components.

From Fig. 4 it is obvious that the power consumption of a coherent transciever with minimal DSP is dominated by the fixed power consumption of optical components such as laser and modulator. This indicates that the extra power consumption associated with improving the performance for higher symbol rates actually can lead to a decrease in overall energy use per bit. Nevertheless, modulator power consumptions can be expected to decrease when new materials with low $V_\pi$ are developed and integrated optical frequency combs is likely to lead to a significant power reduction of light source power consumption, which makes the issue of the power consumption of the minimum DSP needed in coherent interesting in a long term perspective.

## Conclusions

We have experimentally demonstrated a minimum-DSP 5 GBaud coherent link and estimated the power consumption of the minimum DSP by extrapolating the power consumption values from a similar structure ASIC implementation. We also investigate the trade-off between performance and power consumption associated with adding an extra equalizer and allowing higher symbol-rates. We find that with todays coherent transceiver technology, power consumption is limited by optics in the short-reach limit.

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