Weak Coherent State Homodyne Detection with Sequential I-Q Measurements

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Abstract: We design and implement an optical phase estimator for carrier synchronization of a homodyne receiver for weak coherent states, based on sequential I-Q measurements. We report experimental results on performance in BER and phase-number uncertainty.

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1. Introduction

Homodyne optical reception at the telecommunications wavelength band has been studied for more than three decades, due to its unique features concerning the use of complex amplitude modulations that allow improved spectral efficiency and lower photon numbers for a given bit error rate (BER); also when a strong local oscillator (LO) is used, standard quantum limited (SQL) reception is attainable. Furthermore, the use of constant envelope formats, in opposition to traditional on-off keying (OOK), is more tolerant to non-linear effects in the fiber.

Homodyne detection is sensitive to the instantaneous field amplitude and can provide single quadrature measurements only limited by the signal quantum noise. However it requires accurate synchronization of the optical carrier, as the optical phase noise in signal and LO, as well as fluctuations in the thermo-mechanical state of the fiber and other inline components impose considerable challenges. Numerous contributions have been reported in the analysis of the fundamental bounds on the carrier phase estimation parameters for classical channels and diverse synchronization structures have been proposed [1]. For the case of suppressed carrier modulations Costas loops or decision-directed loops are commonly used, based on the simultaneous detection of the received field quadrature using 90° optical hybrids requiring 2 balanced homodyne detectors (BHD).

Recently diverse new applications of homodyne detection techniques have been appearing at the optical telecom band that work with photon number substantially lower than those used in classical transmission, such as quantum cryptography (continuous variables, decoy states and suitable protocols), long distance free space communications, highly sensitive sensors and homodyne tomography that operate with very few average photons per observation time. Therefore the estimation technologies for quantum detection constitute a subject of fundamental research. The synchronization bounds have been studied since the pioneer works by Helstrom [2], dealing with the uncertainty limits in the quadrature measurements. As in any quantum channel, simultaneous in-phase (I) and quadrature (Q) measurements cannot be performed without detection impairments, we propose a sequential measurement technique that performs sequential I-Q measurements of weak coherent states (WCS) using a single BHD by alternatively switching the phase of the LO, at the expense of requiring twice the bit rate.

2. System Implementation

We have designed and implemented an optical phase estimator that performs carrier synchronization of a binary-phase-shift-keying (BPSK) homodyne receiver and demodulates the phase-encoded information as shown in Fig. 1. The general feedback loop based on a simplified version of a maximum-a-posteriori probability (MAP) phase estimator approach [3] is suggested in [4] for the classical channel. The carrier-tracking loop samples the I and Q of a symbol alternatively; constituting a switched optical Costas loop synchronizer.

![Fig. 1 Experimental setup of the sequential I-Q measurements using balanced homodyne detection and the computer-aided Costas loop](image)

After photo-detection, the phase control stage is implemented in discrete time after A/D conversion: a digital algorithm for loop filter and integration is implemented; and D/A conversion is used to control the phase of the LO.
The values used to obtain the bandwidth, loop gain, and the time constants are calculated from the different system parameters such as laser wavelength, line-width, and the gains of the loop components corresponding to the detection noise and dynamics of the phase fluctuations. We get the recursive differential equations by calculating the time constants of an electrical low-pass filter in the analog domain and then using bilinear transformations to get the transfer function in the z-domain.

The I and Q components of the pseudo-random sequence are detected alternatively and the A/D and the D/A converters are used to interface the electronic circuit and the computer programs. We repeat the procedure to obtain the difference equation of an integrator to emulate the optical voltage-controlled-oscillator (VCO). The external piezo-driver fiber actuator allows a dynamic range of phase shifter \([-8\pi, 8\pi]\) and a response time of several milliseconds.

3. Experimental measurements
We use an 1550nm ILM (integrated laser/modulator) electro-absorption modulated light source to generate laser pulses of \(5ns\) at \(8MHz\). WCS signal pulses produced by strong attenuation and LO pulses are polarization-aligned in an interferometer constructed by polarization maintaining components. BPSK on the WCS signal is produced with electro-optical modulator (EOM) with the average signal photon number \(N_S\), the balanced homodyne detection results in [2]:

\[
BER = \left(\frac{1}{2}\right)erfc\left(\sqrt{2N_S}\right)
\]

Although an operator for the phase is not defined, the Heisenberg uncertainty product for quadrature measurements is usually expressed into a photon-number uncertainty product of the standard deviations of coherent states \(\Delta N_{\Delta \theta} \geq \frac{\lambda}{2}\).

We have performed measurements of signal pulses of 0.02-3.0 photons/bit with strong LO pulses so that the quantum noise was of the order of 10dB above the thermal noise level. For each measurement we have taken 229376 samples to calculate the average photon numbers \(N_S\) according to the mean envelope values, the system parameters of the Costas loop are then automatically readjusted.

We have obtained the standard deviations from the phase statistics and the BER by comparing the values obtained after the A/D converter with the transmitted symbols. As shown in Fig. 2(a) the measured standard deviations of I signal are higher than those of Q signal due to the quantification error of the A/D converter. Also the laser residual impurity and the slight imbalance of the photo-diodes degrade the system performance. The measured BER in Fig. 2(b) is slightly higher than the theoretical values due to the imperfect modulation and the residual polarization mismatch.

4. Conclusion
We have implemented an experimental setup for weak coherent state homodyne detection at 1550 nm. We designed a computer-aided Costas loop for phase synchronization by using sequential I-Q measurements with very low photon numbers. We have measured the post-detection BER and analyzed the phase-number uncertainty by measuring respectively the I, Q statistics. As to improve the system performance in term of BER we presently work on a double-threshold detection scheme for specific applications [5] such as cryptosystems.

5. References