Optical homodyne PSK receiver: Phase synchronization by maximizing baseband signal power

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Optical homodyne receivers are very suitable for free-space laser communications, owing to their high sensitivity and frequency selectivity. When realizing a homodyne receiver, synchronizing the local laser oscillator's phase to that of the incoming communication signal is known to be a difficult problem.

So far, three synchronization concepts have been experimentally verified: (a) the pilot carrier concept [1], which adds a small residual carrier to the communication signal and requires the receiver's front-end to be DC-coupled; (b) the Costas loop receiver [2], whose front-end may be AC-coupled, but which requires an optical 90° hybrid instead of a simple 180° hybrid; (c) the syncbit concept [3], which avoids the problems of the above-mentioned schemes by inserting extra bits, shifted in phase by 90°, into the data stream. This measure, however, needs a rather complex digital processor to extract the phase error signal.

Following the syncbit concept, two other schemes have been proposed: Both the switched residual carrier method [4] and the modulated residual carrier method [5] can be implemented with a 180° hybrid and an AC-coupled front-end, but require special modulation electronics in the transmitter.

We propose a solution that offers the same advantages as the syncbit and residual carrier concepts, yet requires less complex electronics in the receiver and no special modulation circuits in the transmitter. In fact, the power of the front-end's output signal can be used as an indicator of the phase difference between the communication signal and the local oscillator signal (see Fig. 1).

To derive this simple relation, we assume that the 180° hybrid is fed by the communication signal and the local laser oscillator signal, which are represented by the complex optical fields

$$\boldsymbol{e}_s(t) = E_s\, e^{j(\phi_s + \boldsymbol{d}(t))} \quad \text{and} \quad e_l = E_l\, e^{j(\phi_l)} \quad , \tag{1}$$

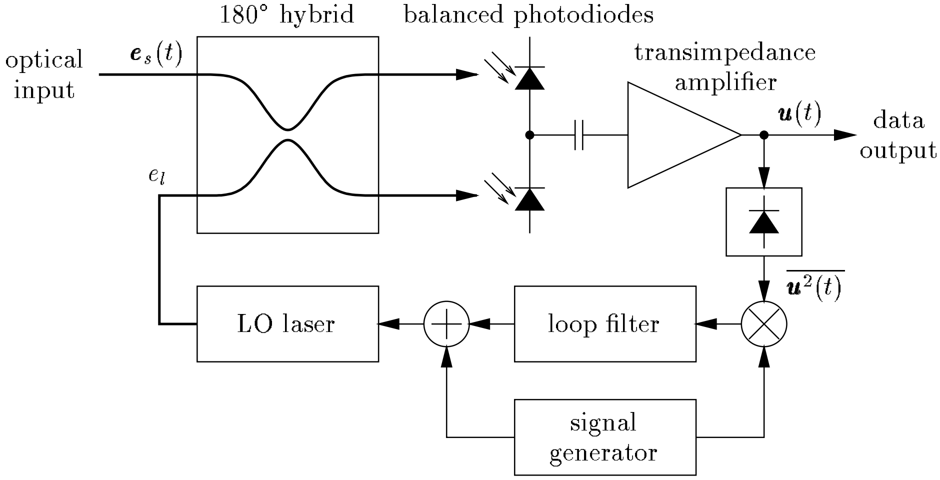

Figure 1: Block diagram of an optical homodyne receiver maximizing the baseband signal power

respectively. E_s and E_l denote the field amplitudes, ϕ_s and ϕ_l are the instantaneous phases of the unmodulated transmit laser output and the local oscillator laser output, and $\boldsymbol{d}(t)$ is the stochastic modulation signal varying between $\pm\pi/2$. It can be shown that the output of the electrical power sensor shown in Fig. 1 is

$$\begin{aligned} \overline{\boldsymbol{u}^2(t)} &= I_0^2 \left[\frac{\alpha+\beta}{2} + \frac{\alpha-\beta}{2}\cos 2(\phi_s - \phi_l)\right] \quad \text{with} && (2) \\ \alpha &= \overline{[z(t) * \cos \boldsymbol{d}(t)]^2} \quad , && (3) \\ \beta &= \overline{[z(t) * \sin \boldsymbol{d}(t)]^2} \quad , \quad \text{and} && (4) \\ I_0 &= \frac{S_1 + S_2}{2} E_s E_l \quad , && (5) \end{aligned}$$

where the overline and the asterisk indicate bit averaging and convolution, respectively. S_1 and S_2 denote the photodiodes' responsivities and $z(t)$ is the impulse response of the the AC-coupled transimpedance amplifier. Eq. (2) implies that the power sensor's output only depends on the phase difference and varies between αI_0^2 (minimum) and βI_0^2 (maximum).

In order to maintain the desired phase difference $\phi_s - \phi_l = \pm\pi/2$,[1] i.e. the state where the maximum baseband signal power is observed, a dither method can be used. To this end, the phase of the local laser oscillator signal is dithered sinusoidally by a small amount (e.g., 0.1rad) at a frequency above the required control loop bandwidth,[2] but well below the data rate. The resulting oscillation of $\overline{\boldsymbol{u}^2(t)}$ is synchronously demodulated, resulting in a sinusoidal phase detector characteristic. The output of the synchronous demodulator is fed into a loop filter, which drives the frequency control port of the local laser oscillator — thus closing the optical phase-locked loop.

The values of α and β depend only on the frequency responses of the phase modulator and optical front-end. For reasonably fast optical phase modulators, $\boldsymbol{d}(t)$ should be near $\pm\pi/2$ for most of each bit period. Hence, a sufficiently high extinction ratio

$$\frac{\left[\overline{\boldsymbol{u}^2(t)}\right]_{max}}{\left[\overline{\boldsymbol{u}^2(t)}\right]_{min}} = \frac{\beta}{\alpha} \gg 1 \tag{6}$$

and stable loop operation should be achievable in practice.

To conclude, phase synchronization by maximizing baseband signal power is less complex than previously proposed strategies, while still offering the key advantages (180° hybrid, AC-coupled front-end).

References

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[1] Data signal polarity is not preserved.

[2] If the local laser oscillator does not have a sufficiently fast internal modulation capability, an external phase modulator has to be used.