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INFLUENCE OF INTERCHANNEL INTERFERENCE ON OPTICAL PHASE DIVERSITY FSK SYSTEMS

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Abstract. In this paper, the performance of phase diversity FSK system in the presence of thermal noise, laser phase noise and interchannel interference is calculated. It is shown that interchannel interference lead to significant performance degradation for coherent systems. Obtained results are shown graphically.

1. Introduction

Digital coherent optical transmissions have received much attention in recent years because of many potential advantages over IM/DD systems. It has been well recognized that ASK, FSK are the most suitable modulation schemes in coherent optical transmission systems using light sources with significant linewidth. The receiver structures can be either heterodyne or homodyne. Both structures can have the same performance. The phase diversity structure has the advantage of needing only baseband signal processing electronics. This is especially important in high bit rate systems where the IF frequency required for heterodyne operation may be well into multi GHz region.

Phase diversity tecnique is not without its own problems. Firstly, the signal processing electronics is more complex and any gain and/or delay mismatches among branches can degrade the system performance considerably. Secondly, since the receiver has at least 2 or 3 branches and optical hybrid is lossy, the effective local oscillator power at each photodetector is reduced and therefore the preamplifier thermal noise may not be negligible.

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This is especially the case for FSK due to the large modulation index needed when the laser sources have significant linewidths.

The object of this paper is to analyze the 2-branch phase diversity FSK receiver taking into account thermal noise [1], laser phase noise [2] and interchannel interference. We present the system model including various noise sources and carry out the analysis to obtain an expression for the system bit error rate (BER). All of the assumptions and approximations are stated explicitly. Numerical results for a typical medium speed system are obtained under a wide range of linewidth and local oscillator power. Interchannel interference is presented as a sine wave with Gaussian distributed random phase. The degradation of system performances due to thermal noise, laser phase noise and interchannel interference is significant and obtained results are discussed in the conclusion.

2. Receiver performance

The basic optical phase diversity FSK two-branch phase diversity receiver is shown on Fig.1.

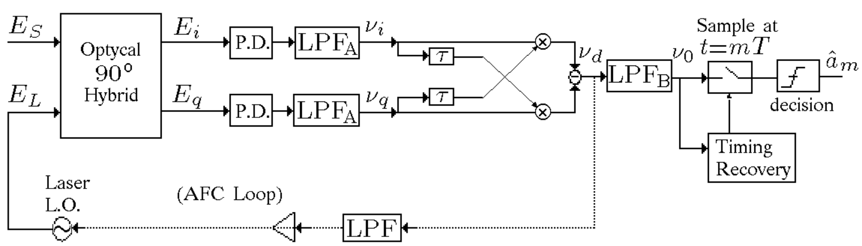

Figure 1. Block diagram of optical phase diversity FSK receiver.

The received optical signal $E_S(t)$ is mixed at the $90°$ optical hybrid with the local oscillator signal $E_L(t)$. The optical hybrid of the FSK two–branch phase diversity receiver inputs are:

$$\begin{aligned} E_S(t) = &\sqrt{2P_S l}\cos(\omega_c t + \phi_m(t) + \phi_t(t)) \\ &+ \sqrt{2P_i l}\cos(\omega_c t + \phi_i(t)) \end{aligned} \tag{1}$$

$$E_L(t) = \sqrt{2P_L l}\cos(\omega_c t + \phi_L(t)) \tag{2}$$

where

- $\phi_t(t)$, $\phi_i(t)$ and $\phi_L(t)$ denote laser phase noises of useful signal, interchannel interference and local oscillator, respectively;
- P_S: received optical signal power;
- P_L: L.O. power;
- l: loss in optical hybrid;
- ω_c: center frequency.

The term $\sqrt{2P_i l}\cos(\omega_c t + \phi_i(t))$ in (1) denotes interchannel interference.

We assume that the baseband message signal is of the form

$$m(t) = \sum_{k=-\infty}^{\infty} a_k p(t - kT)$$

where $a_k = \pm 1$, and $\{a_k\}_{k=-\infty}^{\infty}$ is a random sequence with no correlation between different symbols. $p(t)$ is a suitable pulse waveform that is properly selected to facilitate the recovery of a_k's. In a FSK system, the angle modulation $\phi_m(t)$ is assumed to be:

$$\begin{aligned}\phi_m(t) &= 2\pi f_d \int_0^t w(t')dt' \\ &= 2\pi f_d \int_0^t [a_k p(t' - kT)]dt'\end{aligned} \tag{3}$$

The optical hybrid produces two signals:

$$\begin{aligned}E_i(t) &= \sqrt{P_S l}\cos(\omega_c t + \phi_m(t) + \phi_t(t)) \\ &\quad + \sqrt{P_i l}\cos(\omega_c t + \phi_i(t)) + \sqrt{P_L l}\cos(\omega_c t + \phi_L(t))\end{aligned} \tag{4}$$

$$\begin{aligned}E_q(t) &= \sqrt{P_S l}\cos(\omega_c t + \phi_m(t) + \phi_t(t)) \\ &\quad + \sqrt{P_i l}\cos(\omega_c t + \phi_i(t)) + \sqrt{P_L l}\sin(\omega_c t + \phi_L(t))\end{aligned} \tag{5}$$

Both signals (4) and (5) are converted into electric signals by photodetectors with responsivity $R[A/W]$ and then AC coupled to the low–pass filters, $\mathrm{LPF_A}$, to remove the DC component and high frequency noises.

At the outputs of I and Q channel low pass filters, we have:

$$\begin{aligned}\nu_i(t) &= c_1\cos(\phi_m(t) + \phi_{N_1}(t)) + c_2\cos(\phi_m(t) + \phi_N(t)) \\ &\quad + c_3\cos(\phi_N(t) - \phi_{N_1}(t)) + n_i(t)\end{aligned} \tag{6}$$

$$\nu_q(t) = c_1 \cos(\phi_m(t) + \phi_{N_1}(t)) - c_2 \sin(\phi_m(t) + \phi_N(t)) + c_3 \sin(\phi_N(t) - \phi_{N_1}(t)) + n_q(t) \tag{7}$$

where:

$$c_1 = Rl\sqrt{P_i P_s},$$
$$c_2 = Rl\sqrt{P_L P_s},$$
$$c_3 = Rl\sqrt{P_i P_L},$$
$$\phi_{N_1}(t) = \phi_T(t) - \phi_i(t) = 2\pi \int_0^t f_{N-1}(t')dt',$$
$$\phi_N(t) = \phi_T(t) - \phi_L(t) = 2\pi \int_0^t f_N(t')dt'$$

The combined noises $f_N(t)$ and $f_{N_1}(t)$ are zero–mean white Gaussian processes with p.s.d. $\Delta\nu/2\pi$ and $\Delta\nu_1/2\pi$, respectively.

Frequency demodulation is accomplished by using the "delay and cross–multiplying" circuit. The demodulator output is given by:

$$\nu_d(t) = \nu_i(t)\nu_q(t-\tau) + \nu_i(t-\tau)\nu_q(t) \tag{8}$$

Since in practical implementation τ is usually taken to be much smaller than the bit duration T, we may expand $\nu)i(t-\tau)$ and $\nu_q(t-\tau)$ in series of τ and retain only the first order terms. Under this assumption we have [1]:

$$\nu_d(t) = s_d(t) + (n_{df}(t) + n_{df_1}(t) + n_{dmix}(t) + n_{dshot}(t)) \tag{9}$$

where $\nu_d(t)$ is seen to contain a "signal" component and various "noise" components.

The following assumptions are made in order to carry out an approximate analysis of the receiver performance:

1) The timing recovery circuit works perfectly so that sampling of $\nu_d(t)$ occurs at $t = mT$.
2) All the noise processes $n_i(t), n_q(t), f_N(t), f_{N_1}(t)$ are stationary, zero mean and mutually independent.
3) The effect of $\mathrm{LPF_B}$ is to limit the wide–band random processes to a bandwidth $1/T$ while leaving their mathematical forms unchanged.
4) The message signal $m(t)$ is also treated as stationary random proces with zero mean and p.s.d. $|p(f)|^2/T$. $m(t)$ is independent of other noise terms.

Therefore, for the diversity output at the m-th decision we have

$$\begin{aligned}\nu_0(mT) = &\pm 2\pi\tau f_d c_2^2 + (n_f(mT) + n_{f_1}(mT) \\ &+ n_{0mix}(mT) + n_{0shot}(mT))\end{aligned} \tag{10}$$

The variances of the noises are:

$$\begin{aligned}
&\mathrm{Var}\{n_f(mT)\} = (c_2^2 + c_3^2)^2 4\pi\tau^2 \Delta\nu f_b \\
&\mathrm{Var}\{n_{f_1}(mT)\} = c_3^4 4\pi\tau^2 \Delta\nu_1 f_b \\
&\mathrm{Var}\{n_{0shot}(mT)\} = \frac{32(\pi\tau f_b^2 N_0)^2}{3} \\
&\mathrm{Var}\{n_{0mix}(mT)\} = \tau^2\{2 f_b \pi \Delta\nu (c_1^2 c_2^2 + c_1^2 c_3^2 + 4 c_2^2 c_3^2) \\
&+ 2 f_b \pi \Delta\nu_1 (c_1^2 c_2^2 + 2 c_1^2 c_3^2 + c_2^2 c_3^2) + 2\beta^2 f_b^2 \pi^2 (2 c_1^2 c_2^2 + c_1^2 c_3^2 + c_2^2 + c_3^2) \\
&+ (\frac{8}{3} c_1 c_3 f_b^2 \pi \Delta\nu_1 (3a + b f_b^2) + 8 c_1 c_3 f_b^3 \pi^2 (\frac{a}{3} + 2b\frac{f_b^2}{5}) \\
&+ 8 f_b^3 \pi^2 (c_1^2 + c_2^2 + c_3^2)(\frac{a}{3} + 2b\frac{f_b^2}{5}) + 4 c_1 c_2^2 c_3 f_b \pi (2\Delta\nu + \beta^2 f_b \pi) \\
&+ \frac{8 f_b^2 \pi (3a + b f_b^2)((c_2^2 + c_3^2)\Delta\nu + (c_1^2 + c_3^2)\Delta\nu_1 + \beta^2 c_1^2 f_b \pi + \beta^2 c_2^2 f_b \pi))}{3 e^{f_1^2(\Delta\nu^2 + \Delta\nu_1^2)/\pi^2}}\}
\end{aligned} \tag{11}$$

where: $a = qRP_L l/2$, $b = 4\pi^2 C_T^2 S_E$, and $\beta = f_d/f_b$ is modulation index.

The sample value $\nu_0(mT)$ is approximately Gaussian distributed [2] with mean value $\pm c_2^2\tau 2\pi f_d$. According to previous approximation bit error rate can be evaluated as

$$\begin{aligned}
BER =& Q\left[\frac{c_2^2 \tau 2\pi f_d}{\sqrt{\mathrm{Var}\{\nu_0(mT)\}}}\right], \\
Q(x) =& \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{\alpha^2}{2}} d\alpha
\end{aligned}$$

The BER is calculated and some results are shown on Fig.2.

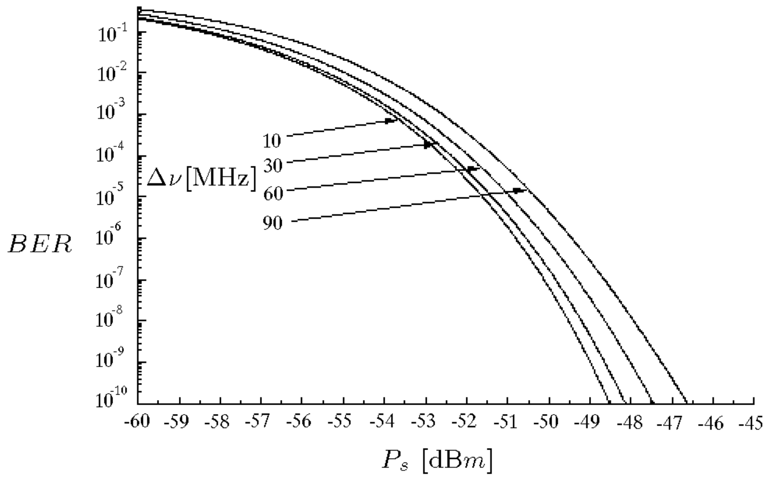

Figure 2. Bit error rate (BER) v.s. received optical power (P_s) for data rate $f_b = 150$ Mbit/s, $f_d = 275$ MHz.

3. Conclusion

Using some reasonable approximations we have analyzed the performance of optical phase diversity FSK receivers. We took into account the influence of various noises such as thermal noise which could not be eliminated using filters, laser phase noise and influence of interchannel interference. It may be seen that degradation of BER becomes significant in comparision with BER for the phase diversity FSK system when interchannel interference is not present [1,2]. Hopefully this work will be a basis for many further investigations on this very promising optical coherent technique.

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