Coding to Relax Laser Linewidth Requirements for Multichannel CPFSK Coherent Optical Communications

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Abstract

A study of the multichannel coherent CPFSK communication system employing Reed-Solomon codes is reported. The crosstalk between adjacent channels, the impact of the laser phase noise, and selection of the optimum code rate are investigated. By applying a suitable coding scheme, the laser linewidth can be greatly relaxed, and the receiver sensitivity will be remarkably improved. A 100 Mbit/s system is used to verify the coding benefit. The results show that the impact of the laser linewidth can be largely alleviated by applying a (255, 223) Reed-Solomon code. When the linewidth is fixed ($\Delta\nu T = 2\%$), this code can improve the receiver sensitivity by more than 15 dB.

1 Introduction

With recent great advances in coherent optical communication technology, many applications for coherent systems, for example, broadband networks, are now being considered in many places [1]. The multichannel coherent optical communications which may transmit many channels simultaneously have been demonstrated [2-4]. In a multichannel system, the continuous-phase frequency shift keying (CPFSK) optical heterodyne with delay demodulation is attractive because: it provides for direct modulation of laser diodes, has reasonable linewidth requirements [5], and leads to close channel spacings [3]. Since the CPFSK delay demodulation scheme uses signal light phase information, high receiver sensitivity is expected. However, the performance of coherent optical receivers is degraded significantly by the phase noise of the semiconductor lasers [6]. Hence, the linewidth requirement is major concern in coherent optical communication applications, especially in multichannel CPFSK systems [5].

Currently to overcome this problem, one either uses the lasers with very narrow linewidth or adopts a large modulation index to avoid phase noise influence. The lasers with narrow linewidth are expensive and difficult to fabricate. For applications in local area networks, the low cost distributed feedback (DFB) lasers with typical linewidth of 50 MHz still can not be used without significant sensitivity degradation. On the other hand, with the modulation index increment, the IF spectrum is broadened and the required IF bandwidth becomes large. In this case, the increase of IF noise degrades the receiver sensitivity.

However, it is well known that error control codes (ECC) provides coding gain at the expense of increasing channel bit rate. The receiver sensitivity will be improved and the error floor can be eliminated by applying error control codes. In this paper, we will study the feasibility of using Reed-Solomon codes to improve receiver sensitivity and to relax the laser linewidth requirements in a multichannel CPFSK system with delay demodulation.

2 Receiver model and basic error rate expression

2.1 Receiver model

Figure 1 shows a balanced delay-and-multiply CPFSK coherent receiver. The voltage at the input of the band-pass filter (BPF) is given by

$$V_1(t) = S_1(t) + n_1(t) \quad (1)$$

where $S_1(t)$ is the signal with phase noise and $n_1(t)$ is the additive noise including shot noise, thermal noise, and crosstalk. $S_1(t)$ is given by [7]

$$S_1(t) = A \cos \left[2\pi f_{IF} + 2\pi f_d \int_{-\infty}^t b(t_1) dt_1 + \phi_n(t) + \theta \right] \quad (1 \text{ a})$$

where $A = 2R\sqrt{P_S P_{LO}}$;

R is the detector responsivity; P_S and P_{LO} are the powers of the signal and the local oscillator, respectively; f_{IF} is the intermediate frequency; f_d is the frequency deviation; $b(t)$ is a binary signal which is equal to +1 or -1 corresponding to the bit "1" or "0" being transmitted; $\phi_n(t)$ is the combined phase noise of the transmitter and local oscillator lasers; and θ is the random initial phase.

The BPF output voltage is

$$V_2(t) = S_2(t) + n_2(t) \quad (1 \text{ b})$$

where $S_2(t)$ and $n_2(t)$ are the filtered versions of $S_1(t)$ and $n_1(t)$, respectively.

The output voltage of the low pass filter (LPF) is

$$V_3(t) = S_3(t) + n_3(t) \quad (1 \text{ c})$$

where $S_3(t)$ is the signal and $n_3(t)$ is the noise.

The BPF is assumed to have the following transfer function:

$$H(f) = \begin{cases} 1 & f \in [f_{IF} - 0.5B_{IF}, f_{IF} + 0.5B_{IF}] \\ 0 & \text{otherwise} \end{cases} \quad (1 \text{ d})$$

where B_{IF} is the filter bandwidth.

2.2 Noise model

2.2.1 Phase noise

The phase noise $\phi_n(t)$ is a nonstationary Wiener process defined as

$$\phi_n(t) = \int_{-\infty}^t \dot{\phi}(t_1) dt_1. \quad (2)$$

The frequency noise $\dot{\phi}(t)$ can be modelled as a zero-mean Gaussian process with the power spectral density (PSD) given by [8]

$$S_{\dot{\phi}}(f) = 2\pi\Delta\nu \left(\text{rad}^2 \cdot \text{Hz} \right) \quad -\infty < f < \infty \quad (3)$$

where $\Delta\nu$ is the full width half maximum (FWHM) linewidth at the "IF", i. e.

$$\Delta\nu = \Delta\nu_T + \Delta\nu_{LO} \quad (4)$$

where $\Delta\nu_T$ and $\Delta\nu_{LO}$ are the linewidth of the transmitter and local oscillator, respectively.

2.2.2 Additive noise

The additive noise $n_1(t)$ is due to the shot noise of the local oscillator, thermal noise of the receiver, and crosstalk from adjacent channels. The single-sided PSD of $n_1(t)$ is given by [4]

$$S_{n_1}(f) = \eta + S_{CT}(f) \quad 0 < f < \infty \quad (5)$$

where η is the PSD of shot noise and thermal noise, and $S_{CT}(f)$ is the PSD of the crosstalk.

The value of η in a coherent system is [4]

$$\eta = 2qRP_{LO} + i_n^2 \quad (6)$$

where q is the electron charge, and i_n is the thermal noise current.

2.2.3 Crosstalk

Crosstalk modelling is discussed in [3]. The crosstalk PSD can be approximated by the PSD of the signals of the adjacent channels [3], which is given by the following expression for the CPFSK modulation format

$$S_{CT}(f) = A^2 G_{PN}(f) * S_{CPFSK}(f) \quad 0 < f < \infty \quad (7)$$

where $G_{PN}(f)$ is the double-sided PSD of phase noise, $S_{CPFSK}(f)$ is the single-sided PSD of CPFSK modulation, and $*$ denotes the convolution operator. The two PSD's are given by the following expressions [4]:

$$G_{PN}(f) = \frac{\Delta\nu}{\pi} \cdot \frac{1}{\Delta\nu^2 + (2f)^2} \quad -\infty < f < \infty \quad (8)$$

$$S_{FSK}(f) = TS_{\text{norm}}(T(f - f_{IF} - D)) \quad 0 < f < \infty \quad (9)$$

where $T = \frac{1}{R_b}$ is the bit duration, D is the electrical domain channel spacing, and $S_{\text{norm}}(T(f - f_{\text{IF}} - D))$ is the normalized PSD of the CPFSK modulation scheme [4].

2.3 Error rate expression

The error rate for the delay demodulation can be expressed as [9]

$$P = \frac{1}{2} - \frac{1}{2} \rho e^{-\rho} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \left[I_n\left(\frac{\rho}{2}\right) + I_{n+1}\left(\frac{\rho}{2}\right) \right]^2 \cdot \exp\left[-(2n+1)^2 \pi \Delta v \tau\right] \cdot \cos\left[\frac{(2n+1)}{2} \pi(1-\beta)\right] \quad (10)$$

where $\beta = 2m\tau R_b$: modulation index parameter, (11)

τ : delay time,

R_b : data rate,

$m = \frac{2f_d}{R_b}$: modulation index,

$I_n(x)$: the modified Bessel function of the first kind, and signal to noise ratio, ρ , is given by

$$\rho = \frac{2R^2 P_s P_{\text{LO}}}{\eta B_{\text{IF}} + \sigma_{\text{CT}}^2} \quad (12)$$

$$\sigma_{\text{CT}}^2 = \int_{f_{\text{IF}} - 0.5B_{\text{IF}}}^{f_{\text{IF}} + 0.5B_{\text{IF}}} S_{\text{CT}}(f) df. \quad (13)$$

2.4 Effect of phase noise on multichannel system

In a multichannel system, frequency separation (D) must be carefully selected. If D is too small, the system performance will deteriorate due to crosstalk between adjacent channels. It has been shown that the choice of modulation index $m = 1$ has the smallest sensitivity penalty,

and therefore, allows the smallest channel spacing [3, 4]. So we assume $m = 1$ and $B_{\text{IF}} = 2.2 R_b$ in the following discussions.

Figure 2 depicts the impact of the linewidth on a multichannel system; it shows the relative penalty versus the channel spacing for several values of $\Delta v T$. The relative penalty is defined as the sensitivity difference in dB to achieve a given error probability 10^{-9} for fixed $\Delta v T$, when D has a given value and $D = \infty$. It is found that as lasers with larger linewidths are used, channel spacing must be increased in order to maintain that the channel spacing D is equal to $2.2 R_b$ to keep the relative penalty within 1 dB.

3 Analysis of coded system

3.1 Features of coded system

When coding is employed in a multichannel system, there are several factors that influence the overall behavior:

1. The shorter channel bit duration reduces the impact of laser phase noise.
2. The error correcting capability makes the system more tolerable to higher channel bit error rate.
3. Coding is at the expense of increasing channel bit rate, the required IF bandwidth becomes larger, and so does the additive noise.
4. Crosstalk is larger when channel spacing is fixed.

The first two factors have benefits for the coding performance, but on the contrary, the last two factors degrade it. So the selection of code rate is important in a multichannel system. We will determine the code rate that is suitable for multichannel application numerically in the following section.

3.2 Code rate optimization

As the code length and signal power are fixed, the code rate, r , can be optimized such that the overall BER is minimum. We will adopt Reed-Solomon (255, k) codes, the reasons are:

1. The (255, k) RS codes are very powerful, and have a very low misdecode rate [10].
2. RS codes are suitable for high speed operation [10].

The decoded output bit error probability P_e for an (n, k) RS code can be estimated from the following bound [11, 12]:

$$P_e < \frac{2^{q-1}}{2^q - 1} \sum_{j=t+1}^n \frac{j+t}{n} \binom{n}{j} P_{sym}^j (1 - P_{sym})^{n-j} \quad (14)$$

where q = the number of bits in each of the n RS code symbols in a codeword,

P_{sym} = the RS code symbol error probability,

$t = \frac{n-k}{2}$ = number of symbol errors can be corrected in a codeword.

As an example, Fig. 3 shows the BER versus code rate for several values of $\Delta\nu T$, where we neglect thermal noise and use the following parameters: $m = 1$, $R_b = 100$ Mbit/s, $R = 0.84$ A/W, $\tau = 0.5$ T, and $D = 2.2 R_b$. We notice that there exists an optimum code rate

$$\left(r = \frac{223}{255}\right) \text{ for which the BER is minimum.}$$

Note that the curve is relatively sharp near the optimum code rate, this indicates that the coding performance is sensitive to the code rate chosen in the multichannel CPFSK system.

The high rate RS code provides additional advantages with practical consideration [10]:

1. The bandwidth expansion is only 14 percent, so the components of the receiver, for example, amplifier and BPF, could be readjusted to accommodate the slightly higher bandwidth without modification.
2. The high rate RS code is commercially available in satellite systems, and can be easily incorporated in optical communication systems.

3.3 Discussions

Figure 4 depicts the BER versus the receiver sensitivity of both coded and uncoded cases for $\Delta\nu T = 0, 1 \%$, and 2% . We define the coding gain as the ratio of the sensitivity without coding to the sensitivity with coding under the same data rate and at $BER = 10^{-9}$. As shown in Fig. 4, when the laser linewidth increases, the coding gain increases. It indicates that coding can be used to effectively combat the phase noise.

Figure 5 shows the impact of the phase noise on the BER performance in a multichannel system with and without coding for $\Delta\nu T = 1 \%$ and various values of D . As the channel spacing becomes smaller, the uncoded system will lead to an additional deterioration. But in a coded system, the deterioration can be compensated by the code.

The coding gain at $BER = 10^{-9}$ versus $\Delta\nu T$ for several channel spacings is shown in Fig. 6. For a fixed channel spacing, the coding gain increases dramatically as $\Delta\nu T$ increases; on the other hand, for a fixed value of $\Delta\nu T$, coding gain also enhances as channel spacing decreases. So coding is an effective way to combat both phase noise and adjacent channel crosstalk in a multichannel system. As shown in Fig. 6, the coding gain can be larger than 15 dB when $\Delta\nu T = 2 \%$ and $D = 2.2 R_b$.

Fig.7 shows the linewidth relaxing factor versus $\Delta\nu T$ at $D=2.2R_b$. The relaxing factor is defined as follows : $\Delta\nu T=1\%$ (uncoded) and $\Delta\nu T=2 \%$ (coded) have the sensitivity at $BER = 10^{-9}$, then the relaxing factor is 2 for $\Delta\nu T = 1 \%$. We see that the relaxing factor may be larger than 10 ($\Delta\nu T = 0.5 \%$) and decreases as $\Delta\nu T$ increases.

4 Conclusions

In this paper, we illustrate the possibility of relaxing the laser linewidth requirement and improving the receiver sensitivity by using Reed-Solomon codes on a multichannel coherent optical CPFSK delay demodulation system. It is found that the (255,223) RS code is a suitable coding scheme for this channel, and can effectively combat both phase noise and adjacent channel crosstalk.

Taking advantage of the commercially available electronics in satellite system, the high rate ($r=0.875$) RS code can be easily incorporated in optical communication system. By employing this coding scheme, the receiver sensitivity can be remarkably improved, and the laser linewidth requirement can be greatly relaxed. An improvement of more than 15dB at $\Delta\nu T = 2 \%$ and relaxing factor of more than 10 at $\Delta\nu T = 0.5 \%$ are estimated.

In a multichannel system, adjacent channel crosstalk degrades system performance seriously. In this paper it is shown that the coding gain increases as channel spacing decreases, and compensate the sensitivity penalty due to adjacent channel crosstalk.

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Fig. 3: The BER versus (255, k) RS codes under several values of ΔvT with $D = 2.2 R_b$ and $P_i = -64$ dBm

Fig. 5: BER versus receiver sensitivity for both coded and uncoded case under several values of D with $\Delta vT = 1\%$

Fig. 7: Relaxing factor of (255, 239) RS code at $BER = 10^{-9}$ and $D = 2.2 R_b$

Fig. 1: A balanced delay-and-multiply CPFSK coherent optical receiver

Fig. 2: Relative penalty versus normalized electrical domain channel spacing for $\Delta vT = 0, 0.5\%, 1\%$, and 1.5%

Fig. 4: BER versus receiver sensitivity for both coded and uncoded case under several values of ΔvT with $D = 2.2 R_b$

Fig. 6: Coding gain versus linewidth-data rate ratio for several channel spacings at $BER = 10^{-9}$