Using Self-error-correction Code in PWAM Optical Fiber Transmission System

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Abstract: The performance of 2-level pulse amplitude modulation and analogue pulse width modulation (PWAM) system based on self-error-correction code was analyzed. The system performance was evaluated by considering the signal to noise ratio (SNR) of 50 dB for analogue signal transmission and bit error rate (BER) of 10^{-9} for digital signal transmission as a lower bound. Computer simulations show that the receiver sensitivity of PWAM system with self-error-correction code can get 1.1 dB improvement without complexity.

Key words: Optical communication; Pulse width modulation; Pulse amplitude modulation; Repetition code

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0 Introduction

Compared to coaxial cables, single mode optical fibers can support high speed or broadband transmission with large repeater spacing, making them more suitable than coaxial cables for digital communications. However, for some analogue signal transmission system, such digital schemes tend to increase the complexity and cost of transmission systems. Moreover, digital schemes based on Pulse Code Modulation (PCM) need a higher bandwidth than analogue schemes [1]. Thus, for economic reasons and because of the characteristic of original image and sound signals, analogue transmission systems can still find applications. Though in the reality, digital signals (control signal, synchronization signal) should also be transmitted at the same time.

A PWAM optical fiber transmission system, which uses a 2-level Pulse Amplitude Modulation (PAM) and analogue Pulse Width Modulation (PWM) hybrid technique, is proposed in[2-4]. Such a system can simultaneously support digital and analogue communications over the common optical fiber in a cost effective fashion. Researchers from the Belgian Nuclear Research Centre have already proposed to use the PWAM optical communication system in the nuclear reactor for both digital and analogue data transmission between reactor core and the external control room[5-9].

The basic operation principle of the PWAM system is that PWM pulse is used to only carry analogue signal and the amplitude of this PWM pulse stream is further modulated by a nonreturn-to-zero (NRZ) digital signal to achieve the 2-level digital PAM [1-2]. Because of the characteristic of the PWAM modulation[3], it is easy to use self-error-correction code for 2-level PAM signal to improve system performance. In this paper, we analyze the PWAM optical transmission system which uses self-error-correction code. Based on the computer simulation, the results indicate the improvement of the system performance.

1 PWAM optical fiber transmission system

In this paper, we consider a 2-level PAM and analogue PWM system in which the sampling frequency of a PWM signal is $f_s = 1/T$ and bit rate of the digital signal is f_b. Fig. 1 illustrates the input data signal and the composite 2-level PAM and analogue PWM signal at a transmitter. Thus, the PWAM system can simultaneously transmit two-channel digital and analogue signals through a common optical fiber. As described in the above, the PWAM signal contains two distinct amplitudes, i.e., a high level b_1 for the data bit "1" and a low level b_0 for the data bit "0" as shown

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in Fig. 1. For the convenience of performance analysis, optical pulses at a photodetector are assumed to be ideal rectangular. The intersymbol interference between optical pulses is thus zero. Also for convenience, the filter is assumed to be an ideal Low Pass Filter (LPF).

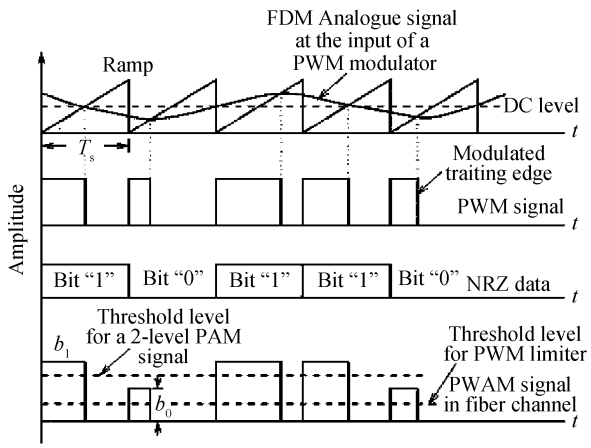

Fig. 1 Illustration of the related waveforms

1.1 PWM system

We first need to consider an analogue PWM optical fiber transmission system only. This corresponds to a special case in which all-zero digital bits are transmitted. The SNR at the output of a PWM demodulator is written as[3,5-7].

$$\mathrm{SNR}=0.98\left[\frac{(\Delta d)^2}{t_r^2}\right]\frac{(\rho G b_0 \pi)^2}{\alpha} \quad (1)$$

$$\alpha=[2eG_2(\rho b_0+I_{dm})+2eI_{du}+S_I]I_{P1}+S_E I_{P2} \quad (2)$$

Where Δd is the variation of pulse duration of a PWM signal. t_r is the rise time or the fall time of the pulse. ρ is the responsivity of a photodetector and b_0 is the average optical power incident on the photodetector. G is the average value of the avalanche gain. e is the electron charge. I_{du} is the dark-current component that is not subject to the avalanche multiplication process and I_{dm} is another component which undergoes the avalanche multiplication process [7]. G_2 is the mean square avalanche gain, i. e. ,$G_2=G^2[KG+(1-K)(2-1/G)]$, here K is the ratio of the ionization coefficients of electrons and holes of an avalanche photodiode. Moreover, S_I is the one-sided noise spectral density of the equivalent input shunt current generator, and S_E is the one-sided noise spectral density of the input voltage noise generator

$$I_{P1}=\int_0^{B_v}\{|H_a(f)H_e(f)|^2+\sum_{m=1}^{+\infty}[|H_a(mf_s-f)H_e(mf_s-f)|^2+|H_a(mf_s+f)H_e(mf_s+f)|^2]\}\,df \quad (3)$$

$$I_{P2}=\int_0^{B_v}\{|H_e(f)|^2+\sum_{m=1}^{+\infty}[|H_e(mf_s-f)|^2+|H_e(mf_s+f)|^2]\}df \quad (4)$$

Where $H_a(f)$, $H_e(f)$ denote the transfer functions of a receiver amplifier and an equalizer, respectively. B_v is the bandwidth of the LPF.

In order to significantly reduce the ISI, the value of guard time is chosen as twice the minimum pulse width T_{min}. For example, we assume that $T_{max}=3T_{min}$.

The T_{min} can be chosen as[3]

$$T_{min}=\frac{T-2t_r}{8} \quad (5)$$

Thus, the relationship between PWM modulation index M and Δd is expressed as

$$\Delta d=\frac{5M(T-2t_r)}{8} \quad (6)$$

2.2 PAM system

Here we analyze the receiver sensitivity for a digital 2-level PAM optical fiber transmission system. To obtain the receiver sensitivity, we need to calculate the total noise power. However, it is much more convenient to refer all the noise power at the input of the receiver amplifier as the input equivalent-current noise power[7]. In this way, the signal-dependent noise is given by

$$\sigma_{sk}^2=2e\rho G_2 b_k B I_1 \quad (7)$$

Where $B=1/T$. I_1 is a weighting constant defined by the input and output waveforms.

The dark-current noise is given by

$$\langle i_d^2\rangle=2e(G_2 I_{dm}+I_{du})B \quad (8)$$

The noise due to the FET-front-end amplifier is given by[2]

$$\sigma_a^2=\frac{4kT}{R}B+2eI_gB+\frac{4kT\Gamma}{3g_m}(2\pi C_T)^2(1+\frac{3f_c}{2B})B^3 \quad (9)$$

where R and C_T are the equivalent total load resistance and input capacitance, respectively. T is the absolute temperature. k is the Boltzmann constant. I_g is the gate leakage current. f_c is the $1/f$-noise corner frequency. The parameter Γ is a numerical constant. g_m is the transconductance.

The total noise power can be expressed as

$$\sigma_k^2=\sigma_{sk}^2+\langle i_d^2\rangle+\sigma_a^2 \quad (10)$$

So the average detected optical power incident on the photodetector is given by[3]

$$\bar{P}=\frac{Q(\sigma_0+\sigma_1)}{2\rho G}+b_0 \quad (11)$$

2 Self-error-correction code in PWAM system

To greatly facilitate the clock recovery and to reduce the receiver complexity, we need to establish a relationship between the sampling frequency f_s of an analogue PWM signal and the bit rate f_b of a data signal as follows[2]

$$f_s=kf_b \quad (12)$$

Where $k\geqslant 1$ is an integer. This is equivalent to using a simple repetition code of two code words (i. e., one of all 0′s and the other of all 1′s) for the 2-level PAM signal[2], so its Bit Error Rate (BER) performance can be improved if the error-correction capability is further exploited.

As we know, repetition code is the simplest code which repeats each codeword some times to get BER improvement. So the minimum distance of a (k, 1) repetition code with length k is equal to k. Such a code can correct t or fewer errors if $k \geqslant 3$, where t is given by

$$t=\left[\frac{k-1}{2}\right] \tag{13}$$

Here $[y]$ denotes the integer part of a real value y.

We can assume that an optical fiber communication channel is memoryless. 2-level PAM optical fiber systems can be also modeled as a binary symmetric channel as shown in Fig. 2 if a threshold level at the receiver is appropriately chosen (this is useful to APD based optical receivers), i. e., $p(0 \mid 1)=p(1 \mid 0)=\mathrm{p}$, where $p(0 \mid 1)$ and $p(1 \mid 0)$ are the probabilities of deciding data bit "0" and bit "1" when bit "1" and bit "0" were sent, respectively. Assume that data bit "1" and bit "0" occur with equal probability, so $p(1)=p(0)=1/2$. Therefore, the BER of a 2-level PAM system without exploiting its error-correction capability is expressed as

$$\mathrm{BER}_{\mathrm{withoutECC}}=p(0 \mid 1)p(1)+p(1 \mid 0)p(0)=p \tag{14}$$

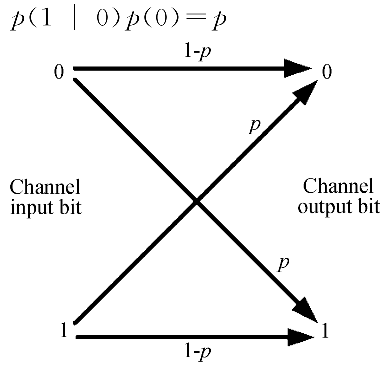

Fig. 2 A binary symmetric channel

When the inherent self-error-correction capability of a (k, 1) repetition code ($k \geqslant 3$) is utilized, the post-decoding BER of this 2-level PAM system is now written as[2]

$$\mathrm{BER}_{\mathrm{ECC}}=1-\sum_{j=0}^{t} C_k^j p^j (1-p)^{k-j} \quad \text{for } k \geqslant 3 \tag{15}$$

Comparing equations (14) and (15), we can immediately find that the BER performance will be improved by inserting a repetition-code decoder at the output of the threshold detector inside an optical PWAM receiver[2], without changing the system configuration, i. e., not increasing the system complexity. This is a significant advantage of the proposed PWAM technique for optical fiber communications.

3 Computer simulation

Fig. 3 compares the BER performance of the proposed 2-level PAM systems without and with exploiting an self-error-correction capability of (k, 1) repetition codes using the same Q factor. The system guarantees the output $\mathrm{BER}=1\times10^{-9}$ with input Q factor is 4.1, 3.3, 2.8 and 2.5 when the repetition codes k is 3, 5, 7 and 9, respectively. So the input BER can even be 4.9×10^{-4} when k is 5 which means the better receiver sensitivity or the larger repeater spaceing. It is clear that the BER of 1×10^{-9} can be achieved using a repetition code even if the channel error probability is high. Therefore, the receiver sensitivity can be improved when this error correction capability is used. However, the same system could require a higher input optical power to guarantee the $\mathrm{BER}\leqslant 1\times10^{-9}$ if the self-error-correction capability is not exploited.

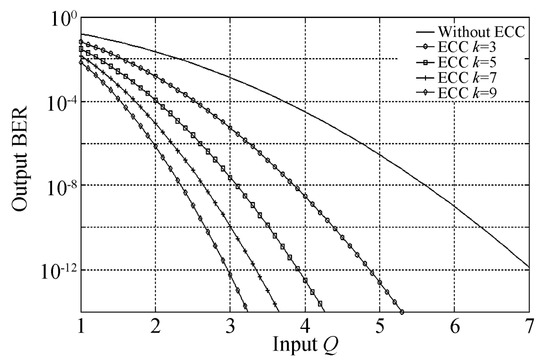

Fig. 3 Input Q vs output BER

In the following calculations, the parameters of InGaAs APD and Si MOSFET are chosen as: $f_s=15$ MHz, $\rho=0.6\ A/W$, $K=0.3$, $I_{\mathrm{du}}=1$ nA, $I_{\mathrm{dm}}=1$nA; and $g_m=30$ mS, $f_c=5$ MHz, $I_g=0.01$ nA. Moreover, the operation temperature $T=300$ K, the modulation index $M=1$ for analogue PWM signal, and the total capacitance $C_T=8$ pF. The minimum pulse width $T_{\min}$ is then equal to 0.1149T. As we know, the noise power become larger when the width of the rectangular pulse get smaller. So in the simulations, we choose the width of the input rectangular pulse as $T_{\min}$ to test the worst performance of the PWAM system. In computer simulations we set SNR = 50 dB for the analogue PWM system and output $\mathrm{BER}=1\times10^{-9}$ for the digital PAM system. The required minimum average optical power of PWM, PAM and PWAM system versus APD gain G is plotted in Fig. 4. The minimum optical power of −52.84 dBm and −48.54 dBm are obtained with G of 21 and 22 for PWM and PAM system, respectively. However the minimum optical power of the whole PWAM system is −50.17 dBm with optimum $G=20$.

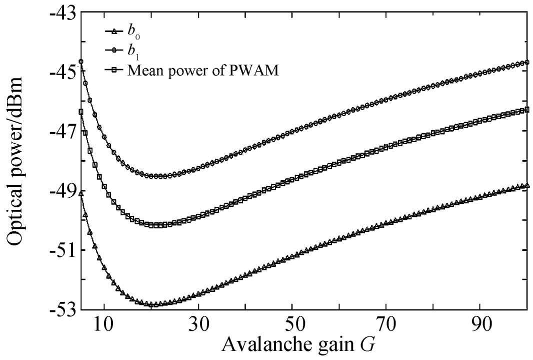

Fig. 4　Minimum optical power of PWM, PAM and PWAM system without ECC

The receiver sensitivity of PWAM system with error correction code (ECC) versus G is plotted in Fig. 5. We get a receiver sensitivity of −50.91 dBm, −51.25 dBm, −51.46 dBm and −51.6 dBm with the same $G=21$ when using the ECC. When we choose repetition code $k=5$, the receiver sensitivity can get 1.1 dB improvement than the system without ECC. The cost is the decrease of the digital bit rate from 15Mb/s to 3Mb/s which is also enough to transmit the control signal and synchronization signal. We can also increase the sampling frequency, which is easy to realize, to get the higher the bit rate. From the computer simulation, we can see when k becomes larger, the receiver sensitivity gets improvement. But the data rates decrease at the same time. So in a PWAM system which uses self-error-correction code, we should simultaneously consider data rates and receiver sensitivity to get an optimum k. In our calculations we set the optimum $k=5$.

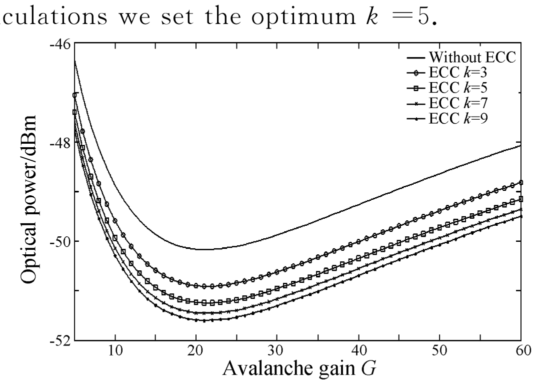

Fig. 5　Receiver sensitivity of PWAM system with ECC

4　Conclusion

Because of the PWM and PAM modulation method from Equ. (12), self-error-correction code can easily be adopted into PWAM system[2]. The error correction effect has been estimated based on the improvement in receiver sensitivity. Compared with a conventional optical fiber transmission system, the proposed PWAM system with repetition code does not have a high complexity. Though digital and analogue signals can be simultaneously transmitted over a common optical fiber with receiver sensitivity of −51.25 dBm. Computer simulation results show the effectiveness of the proposed transmission technique.

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自纠错码在PWAM光纤传输系统中的应用

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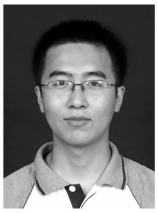
摘　要:基于自纠错码的二级脉冲幅度调制与脉冲宽度调制(PWAM)光纤传输技术,对系统中的接收机灵敏度进行了分析.在模拟信号信噪比不小于50 dB,数字信号误码率不低于10^{-9}情况下进行仿真.结果表明,在没有增加系统复杂性的前提下,使用自纠错码时二级脉冲幅度调制以及脉冲调制光纤接收机灵敏度将有1.1 dB的改善.

关键词:光通信;脉冲宽度调制;脉冲幅度调制;重复码



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