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Impact of FWM on Manchester Coded DPSK WDM Communication Systems

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The performance of Manchester-coded DPSK optical wavelength division multiplexing (WDM) systems using a stochastic approach is evaluated taking into account the shot noise and the four-wave mixing (FWM) caused by fiber nonlinearities. The result of Manchester-coded system is compared to conventional non-return-to-zero (NRZ) systems for DPSK modulation formats. Further, the dynamic range, defined as the ratio of the maximum input power (limited by the FWM), to the minimum input power (limited by receiver sensitivity), is evaluated. For 1.55 μm 16 channel WDM systems, the dynamic range of DPSK Manchester coded systems shows a 2.1 dB improvement with respect to the NRZ. This result holds true for both dispersion-shifted fiber and conventional fiber; it has been obtained for 10 GHz channel spacing, 1 Gbps/channel bit rate.

Introduction

The performance of optical wavelength division multiplexing (WDM) systems may be degraded by the nonlinearities of optical fibers.[1,2] One important fiber nonlinearity is four wave mixing (FWM). This effect occurs when two or more optical waves at different wavelengths mix to produce new optical waves at other wavelengths. The new optical waves may lead to crosstalk.[3]

Several studies of four wave mixing in WDM communication systems have been published.[4-6] It showed that the FWM crosstalk limits the number of channels, the maximum allowed input power per channel and the channel frequency separation using a stochastic approach.[4] The allowed power per channel, for a given number of channels and a given frequency separation, depends on the fiber dispersion and attenuation. The study took into account FWM only, and neglected other noise sources, such as shot noise. The theoretical and experimental studies describing the system performance degradation due to FWM in a multichannel FSK direct detection transmission system[5] and FSK heterodyne envelope detection system[6] were reported. The system performance evaluation of three channels WDM system was made using the deterministic approach, but a stochastic approach is used in the multichannel system more than three channels. These two papers considered shot noise and showed power penalty due to FWM and input power causing a power penalty of 1 dB. Maximum allowable input power to get a BER 10^{-9} due to FWM was not obtained in these papers. In addition, the bit error rate in all previous studies was calculated under the assumption that the entire power of the interference due to FWM falls into the signal bandwidth.

Our analysis takes into account the shot noise originating from the light detection process and FWM crosstalk resulting from the optical fiber nonlinearity. These two effects limit the transmission distance. We show that Manchester coding reduces the impact of FWM on DPSK WDM systems. Our analysis does take into account the spectral distribution of FWM, and so is believed to be more accurate than previous studies.

The rest of this paper is organized as follows. The system block diagram, receiver output signal, FWM crosstalk and noises are described in Section II. Autocorrelation functions for the NRZ and Manchester codes, the signal-to-noise ratio and bit error rate evaluation are described in Section III. Numerical results

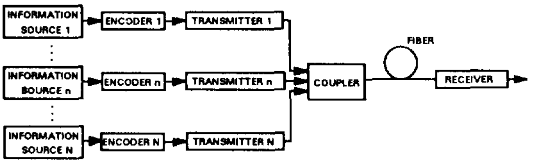

Fig. 1. Block diagram of an optical wavelength division multiplexing system.

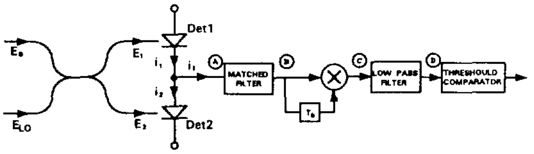

Fig. 2. A Heterodyne DPSK Receiver.

and discussion are contained in Section IV. Finally, Section V contains the conclusions of this paper.

II. Wavelength Division Multiplexing System and Four Wave Mixing

The block diagram of a N-channel optical WDM system employing Manchester coding is shown in Fig. 1. Encoders are used to convert NRZ data to Manchester-coded data. The matched filter is used as a decoder in the receiver. We assume that all transmitters use the DPSK modulation format. The block diagrams of DPSK receivers are shown in Fig. 2. We assume the lowpass filter just removes the second harmonic components resulting from the delay-and-multiply demodulator without changing the baseband components. We assume that the channel separation is large enough to neglect the inter-channel crosstalk.[7]

The balanced receiver output voltage, V_T is[4]

$$V_T(t)=A\{[\sqrt{P_p(t)}+n_c(t)]\cos[\omega_{IF}t+\phi_p(t)]+n_s(t)\sin[\omega_{IF}t+\phi_p(t)]\}+n_0(t) \tag{1}$$

where $P_p(t)$ and $\phi_p(t)$ are the signal power and phase at the fiber input and the amplitude A is given by

$$A=2Ru\sqrt{P_{LO}} \tag{2}$$

where R is the photodetector responsivity, P_{LO} is the local oscillator power and $u=\exp(-a\cdot L/2)$. The shot noise $n_0(t)$ and the in-phase $n_c(t)$ and the quadrature $n_s(t)$ components of crosstalk are given by

$$n_0(t)=n_1(t)-n_2(t) \tag{3}$$

$$n_c(t)=\sum_{\mu,\nu}\sqrt{P_n(t)}\sin\phi_{\mu\nu\rho}(t) \tag{4}$$

$$n_s(t)=\sum_{\mu,\nu}\sqrt{P_n(t)}\cos\phi_{\mu\nu\rho}(t) \tag{5}$$

where $n_1(t)$ and $n_2(t)$ are shot noises originating from the detection process and $P_n(t)$ and $\phi_{\mu\nu\rho}(t)$ are the power and phase change of the optical noise process due to FWM given by

$$P_n(t)=\kappa^2D^2\eta P_{\mu+\nu-\rho}(t)P_\mu(t)P_\nu(t) \tag{6}$$

$$\phi_{\mu\nu\rho}(t)=\phi_\mu(t)+\phi_\nu(t)-\phi_\rho(t)-\phi_{\mu+\nu-\rho}(t)+Arg(L_e) \tag{7}$$

where D is the degeneracy factor. The phases $\phi_{\mu\nu\rho}(t)$ are regarded as independent random variables to simplify the analysis. The parameters κ and the phase mismatch factor η, denotes the ratio of the power of the generated waves without phase matching to their power with phase matching, are given by

$$\kappa=\frac{32\pi^3}{n^2c\lambda}\frac{L_{eff}}{A_{eff}}\chi_{1111} \tag{8}$$

$$\eta=\frac{\alpha^2}{\alpha^2+\Delta k^2}\left[1+\frac{4\exp(-\alpha L)\sin^2(\Delta kL/2)}{\{1-\exp(-\alpha L)\}^2}\right] \tag{9}$$

where L_{eff} is the fiber effective length, A_{eff} is the fiber effective area, n is fiber core refractive index, c is the velocity of light in vacuum, a is the fiber power attenuation constant, χ_{1111} is third order nonlinear susceptibility and Δk is the phase mismatch factor.

III. Coding Methods and BER Evaluation

The matched filter output voltage at the terminal B of Fig. 2 is given by

$$\begin{aligned}V_o(T_b)&=\int_0^{T_b}V_T(t)\cdot h(T_b-t)dt\\&=\int_0^{T_b}S(t)\cdot h(T_b-t)dt+\int_0^{T_b}n(t)\cdot h(T_b-t)dt\end{aligned} \tag{10}$$

where T_b is bit period and $h(t)$ is impulse response of the matched filter and are given by

$$h_{NRZ}(t)=\begin{cases}\cos\omega_{IF}t & \text{for } t\in[0,\ T_b]\\ 0 & \text{for } t\notin[0,\ T_b]\end{cases} \tag{11}$$

$$h_{MAN}(t)=\begin{cases}-\cos\omega_{IF}t & \text{for } t\in[0,\ T_b/2]\\ \cos\omega_{IF}t & \text{for } t\in[T_b/2,\ T_b]\\ 0 & \text{for } t\notin[0,\ T_b]\end{cases} \tag{12}$$

The first term of expression (10) gives the signal and the second term is a zero-mean Gaussian random variable; its variance is given by

$$\sigma^2=\int_0^{Tb}\int_0^{Tb}R_n(t_1-t_2)h(T_b-t_1)h(T_b-t_2)dt_1dt_2 \qquad (13)$$

where $R_n(t_1-t_2)=E[n(t_1)n(t_2)]$ is the autocorrelation function of the noise.

Assume that all channels use the same modulation scheme and have the same power. Then, from expressions (4), (5), (6) and (7), the autocorrelation function of the crosstalk due to FWM is given by

$$R_{FWM}(\tau)=\frac{A^2}{2}\kappa^2P_\rho^3R^3(\tau)\cos\omega_{IF}\tau\sum_{\mu,\nu}D^2\eta \qquad (14)$$

where $R(\tau)$ is the autocorrelation function of each signal. The autocorrelation function of the baseband NRZ and Manchester-coded signals

$$R_{NRZ}(\tau)\begin{cases}1-\dfrac{|\tau|}{T_b} & |\tau|<T_b\\ 0 & |\tau|>T_b\end{cases}$$

$$R_{MAN}(\tau)=\begin{cases}1-3\dfrac{|\tau|}{T_b} & |\tau|<\dfrac{T_b}{2}\\ \dfrac{|\tau|}{T_b}-1 & \dfrac{T_b}{2}<|\tau|<T_b\\ 0 & |\tau|>T_b\end{cases} \qquad (16)$$

Substituting (14) into (13), we obtain the variance of FWM crosstalk:

$$\sigma^2{}_{FWM}=\frac{A^2}{2}\kappa^2P_\rho{}^3\int_0^{Tb}\int_0^{Tb}R'(t_1-t_2)h(T_b-t_1)h(T_b-t_2)dt_1dt_2$$
$$\sum_{\mu,\nu}D^3\eta \qquad (17)$$

The variance of the shot noise;

$$\sigma^2{}_{SN}=qRP_{LO}\int_0^{Tb}h^2(T_b-t)dt \qquad (18)$$

where q is the electron charge.

Therefore the total signal-to-noise ratio γ, defined as the ratio of the signal power to the noise power, is given by

$$\gamma=\frac{A^2T_b{}^2P_\rho}{4(\sigma^2{}_{FWM}+\sigma^2{}_{SN})}=\frac{1}{[2\kappa^2P^2{}_\rho V^2S^2+qW/RT_bu^2P_\rho]} \qquad (19)$$

This equation shows that as the input signal power P_ρ increases, the signal-to-noise ratio γ first increases due to the relative suppression of the shot noise, and then decreases due to the FWM. Thus, at some value of P_ρ, a peak value of γ is reached corresponding to the optimum system performance.

The bit error rate of the heterodyne DPSK system

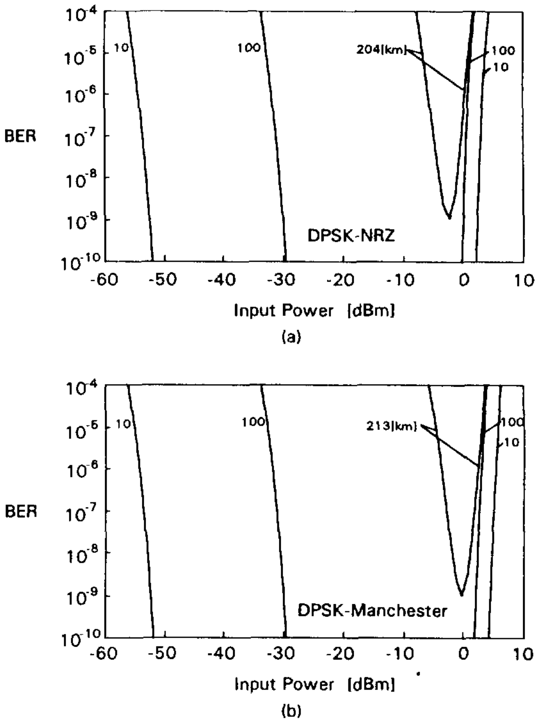

Fig. 3. The bit error rate of a 16 channel DPSK coherent system using dispersion shifted fiber versus optical fiber input power; the parameter is the transmission distance. (a) NRZ-coded system, (b) Manchester-coded system.

Table 1. System parameters

Channel Spacing		10 GHz
Bit Rate		1 Gbps
Wavelength, λ		1.55 μm
Attenuation Coefficient, α		0.25 dB/km
Refractive Index, n	NDS Fiber	1.47
	DS Fiber	1.476
Effective Fiber Core Area, A_{eff}	NDS Fiber	86.6 μm^2
	DS Fiber	51.5 μm^2
Group Velocity Dispersion, C	NDS Fiber	17 ps/(nm·km)
	DS Fiber	1 ps/(nm·km)

can now be found as[8]

$$BER_{DPSK}=\frac{1}{2}\exp\left[-\frac{\gamma}{2}\right] \tag{20}$$

Using expressions (17), (18), (19) and (20), we obtain the numerical value of BER of the DPSK optical multichannel system impaired by the shot noise and the four wave mixing. Fig. 3 shows the BER for the 8 th channel of a 16 channel versus the optical fiber input power for several values of the fiber length; the system parameters are shown in Table 1.

The system dynamic range is defined as the ratio of the maximum input power to minimum input power to maintain BER below 10^{-9}. The Manchester code gives a 2.1 dB larger dynamic range than the NRZ. The minimum power due to shot noise is the same for NRZ and Manchester-coded systems. According to Fig. 3, the maximum transmission distance is 213 km for Manchester coded systems using dispersion-shifted (DS) fiber and 204 km for the NRZ coded system. The corresponding numbers for the system using non-dispersion shifted (NDS) are 250 km and 242 km, respectively. The largest transmission distance is achieved using Manchester-coded DPSK system.

IV. Numerical Results and Discussion

1. Maximum Transmission Length

The maximum transmission length of optical WDM systems is limited by the shot noise and the four wave mixing. The optical fiber input power corresponding to the minimum BER is obtained by differentiating expressions (20) with respect to P_p and setting the derivative equal to zero. The maximum transmission distance is obtained by substituting that value into expressions (20). Fig. 4 shows the maximum transmission length versus the number of channels for ASK and DPSK modulation schemes and coding methods; all calculation are for the worst-case channel (i.e. channel N/2). The four-wave-mixing crosstalk is maximum for that channel. The upper four curves are for the NDS fiber, while the lower four curves are for the DS fiber. All curves show that the maximum transmission length decreases with the number of channels.

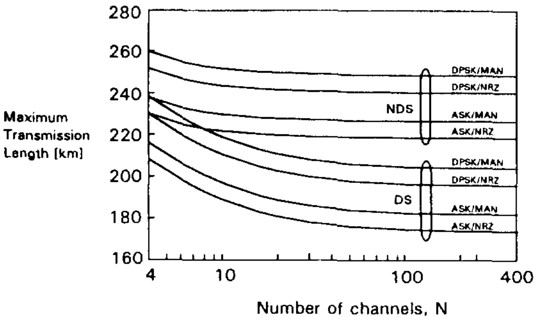

Fig. 4. Maximum transmission length versus number of channels for various modulation schemes and coding methods.

Manchester coded systems have the maximum transmission distance larger than that of NRZ coded system by 8 km for both DPSK and ASK modulation formats; this conclusion is valid for both kinds of fiber. It is interesting that for a large number of channels the NDS fiber outperforms the DS fiber. The reason is that the relatively small core area and improved phase matching due to small group velocity dispersion increase the four-wave mixing crosstalk in the DS fiber as compared to the NDS fiber (the transmission length is limited by the FWM rather than by chromatic dispersion in the particular case considered).

2. Dynamic Range and Power Budget

2.1 Dynamic Range

The fiber input power must be kept between the minimum value P_{min} and the maximum value P_{max} to maintain BER below 10^{-9}. The maximum input power P_{max} is determined by the four wave mixing, and the minimum value P_{min} is determined by the shot noise. The maximum and minimum input powers for 8 th channel of a 16 channels WDM system needed to maintain BER below 10^{-9} are shown in Fig. 5. The upper four curves are the maximum input power for various coding formats and optical fiber types and the lower two curves are the minimum input power for the same coding methods and fiber types. The ratio of the maximum power to the minimum power is defined as the dynamic range, and is an important factor in system design. For example, the dynamic range of a Manchester-coded DPSK system with 1 Gbps bit rate and 100 km non-dispersion sifted fiber is 41.7 dB, as shown in Fig. 5. Fig. 6 shows the dynamic range of a 16-channel WDM system versus the length of optical fiber

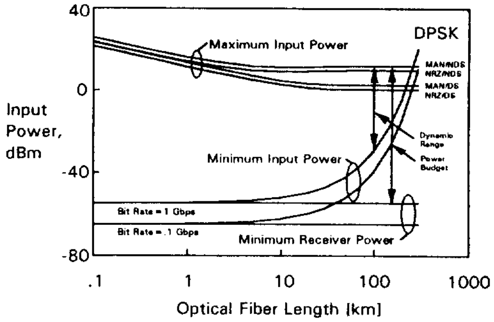

Fig. 5. Maximum input power, minimum input power and system dynamic range and system power budget versus optical fiber length for various fibers and DPSK modulation formats.

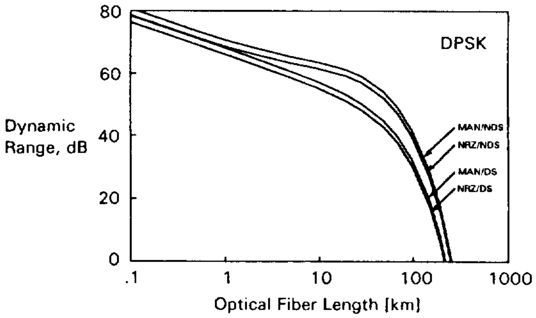

Fig. 6. Dynamic range of a 16 channel WDM system versus optical fiber length for DPSK systems.

for two fiber types and various modulation and coding formats. The curves show that short-distance systems have a large dynamic range of some 70 dB but as the transmission distance increases, the dynamic range decreases, and falls to some 30 dB at 100 km. Manchester-coded DPSK 100 km systems have some 2.0 dB larger dynamic ranges than corresponding NRZ systems.

2.2 Power Budget

The power budget is defined as the ratio of the maximum input power to the minimum receiver power needed to keep BER below 10^{-9}. For example, the power budget of Manchester coded DPSK system for the 8 th channel of a 16 channels WDM system with 1 Gbps and non-dispersion shifted fiber is about 66.7 dB and shown in Fig. 5. The drop of the power budget at long lengths is due to the drop of the maximum allowable input power caused by the four wave mixing. For very long fibers, the maximum power level remains almost the same, and therefore, the power budget remains almost the same. The power budget of DPSK is some 5.5 dB larger than that of ASK system. Manchester coded systems show about 2.0-2.1 dB improvement with respect to NRZ systems. The power budget of systems using NDS fiber is 10.3 dB larger than that of systems using DS fiber.

3. Polarization, Chromatic Dispersion and Interchannel Interference

The strength of crosstalk due to FWM waves depends on the relative state of polarization of the interacting waves. In our analysis, we assume the worst-case in which all the interacting waves are parallel. As a result, FWM crosstalk power is decreased to 1/4 and 3/16 of the value expected for a fixed state of polarization for partially degenerate and the completely nondegenerate channel combinations, respectively.[9] The reduction factor are multiplied to expression (17), the variance of FWM crosstalk, for the degenerate and nondegenerate case in the calculation. In this paper, the case of random polarization is considered, so that all our results apply to systems NOT employing polarization-preserving fiber.

The chromatic dispersion can produce distortion in the demodulated waveform resulting in intersymbol interference in the received signal and reduction of transmission system performance. The chromatic dispersion limitations for coherent system were studied by many authors.[10,11] The receiver sensitivity degradation due to chromatic dispersion has been observed in an FSK transmission experiment at more than 4 Gbits/s.[10] However, transmission experiments from 1 to 2 Gbits/s have shown that the influence of chromatic dispersion on FSK systems is less than that on intensity-modulated system.[11] Receiver sensitivity degradation due to chromatic dispersion depends on the modulation and demodulation schemes used. The transmission distance limit due to chromatic dispersion is some 2,000 km for 1.55 μm non-dispersion shifted ASK and DPSK systems.[12] Since the transmission distance constraints studied in this paper are less than 2,000 km, the impact of chromatic dispersion can be (and is) neglected.

The bandwidth of the Manchester coded signal measured to the first null is twice that of the NRZ bandwidth. If several FDM channels are being transmitted, then a coherent system may suffer a performance degradation stemming from crosstalk generated by intermodulation interference. Prior work showed that balanced receivers are superior to single detector receivers in multichannel environment, and for small penalty (below 1 dB) both time and frequency analysis techniques yield essentially the same results.[7] Based on the results of,[7] the electrical domain channel spacing of NRZ and Manchester coded DPSK systems can be set as 3.0 and 4.6, respectively. The optical domain channel spacing normalized to bit rate is

$$D_{opt}=D_{nel}+2\cdot f_{IF}\cdot T_b \qquad (21)$$

where D_{nel} is normalized electrical channel spacing. When the IF frequency for the Manchester-coded system is selected to be $2/T_b$, Dopt is less than 10. Thus, for all systems considered in this paper, the optical channel spacing of 10 bit rates is adequate. Thus, we select the optical channel spacing to be 10 GHz for all 1 Gbits/s systems investigated in this paper.

VII. Conclusions

The performance of Manchester-coded DPSK optical wavelength division multiplexing (WDM) systems using a stochastic approach is evaluated taking into account the shot noise and the four wave mixing (FWM) caused by fiber nonlinearities. The minimum receiver power is determined by the shot noise, and maximum transmitter power is determined by the four wave mixing.

For 1.55 μm dispersion shifted 16 channel DPSK systems, having 10 GHz channel spacing and 1 Gbps per channel bit rate, the maximum transmission length is about 237 km for NRZ and 247 km for Manchester codes, respectively. The maximum transmission length of the ASK system using non-dispersion shifted fiber is 261 km for NRZ and 271 km for Manchester codes, respectively. The corresponding numbers for DPSK systems are 288 km and 299 km, respectively. The physical reason is that the transmission length is limited by the FWM rather than by dispersion in this particular case.

To maintain system BER below 10^{-9}, the fiber input power must be kept between the maximum value determined by the fiber four wave mixing and the minimum value determined by the receiver shot noise. The ratio of the maximum input power to the minimum input power is defined as the dynamic range. The dynamic range of 100 km Manchester coded systems is some 2 dB better than that of NRZ systems for DPSK modulation formats.

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Manchester Coded DPSK WIDM 통신 시스템에서 FWM의 영향

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Stochastic 접근 방식을 사용한 Manchester 코드 파장분할다중 시스템의 성능이 산탄 잡음과 광섬유 비선형성에 기인한 four-wave mixing을 고려하여 평가되었다. DPSK 변조방식에 대하여 Manchester code 시스템의 결과는 기존의 non-return-to-zero 시스템과 비교된다. 더구나, 최대 입력 전력(FWM에 의해 제한)과 최소 입력 전력(수신 감도에 의해 제한)의 비로서 정의된 dynamic range가 평가되었다. 1.55 μm 16채널 시스템에서 DPSK Manchester 코드 시스템의 dynamic range는 NRZ에 대한 관점에서 2.1 dB의 개선을 보인다. 이 결과는 분산 천이(dispersion-shift) 광섬유와 기존의 광섬유에 대해서 같은 결과를 얻어졌으며 10 GHz의 채널 간격과 1 Gbps/channel bit rate에서 이루어졌다.