Error Performance of D(Q)PSK Signal with Nonlinear Phase Noise and Phase Error

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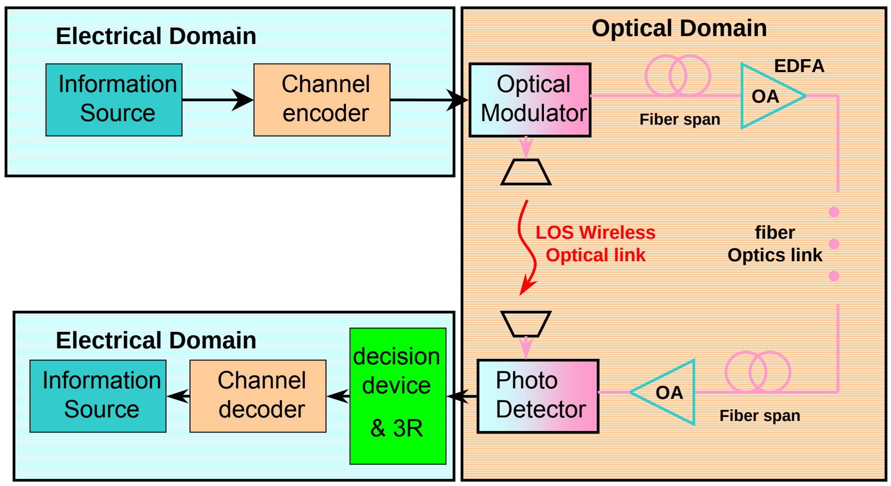
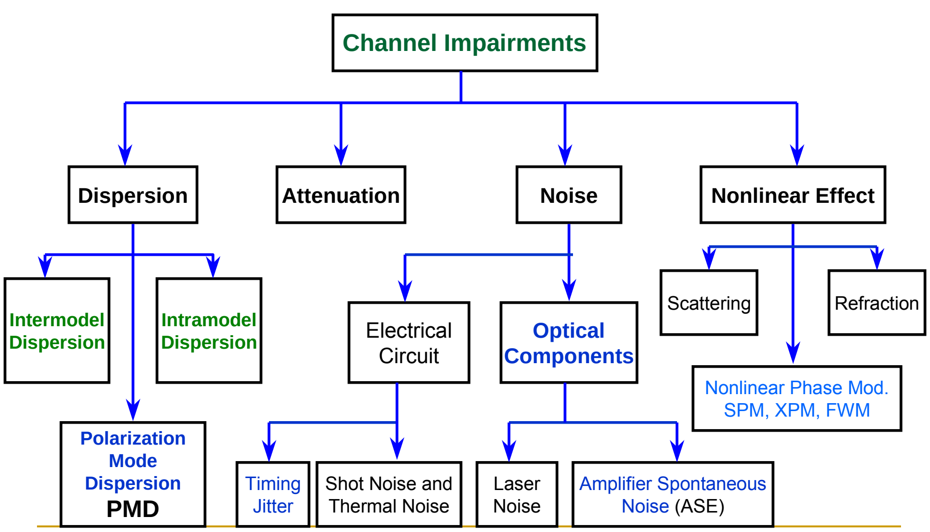
Outline

- Channel Impairment and Transmission Limitation
- DPSK and DQPSK Signal
- Error Performance to phase error
- Error Performance to Self-Phase Modulation
- Conclusions
- Reference

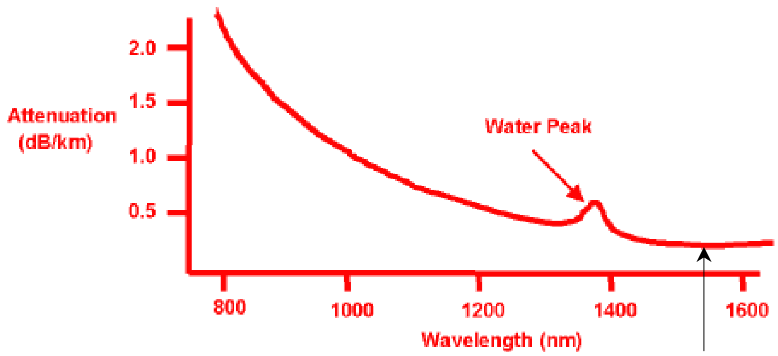
Optical Communication System



Fiber Channel

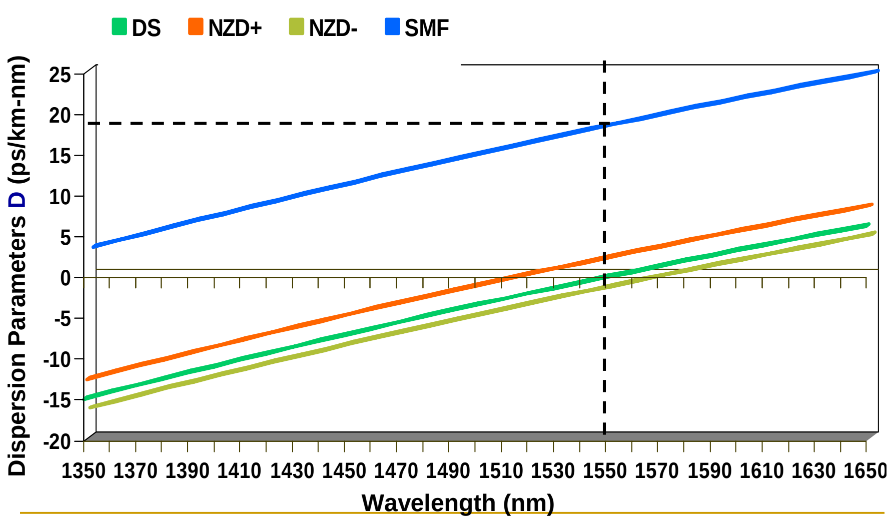


Fiber Attenuation

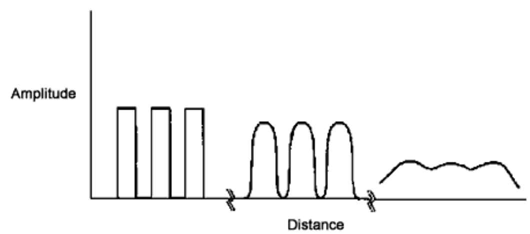


~0.2db/Km
@ 1550nm

Dispersion Profile

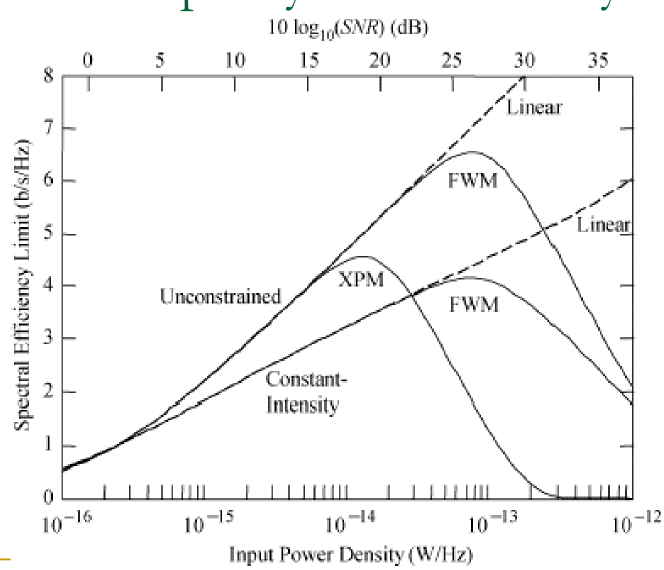


Dispersion caused pulse broaden



e.g.: For 10Gbps system: $\Delta\tau = D \cdot \Delta\lambda \cdot L = 17 * 0.08(nm) * 50(km) = 68$ ps

Channel Capacity of DWDM system[1]



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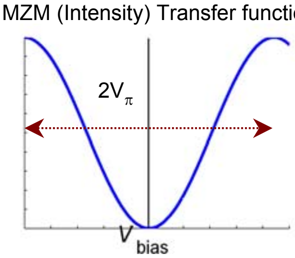
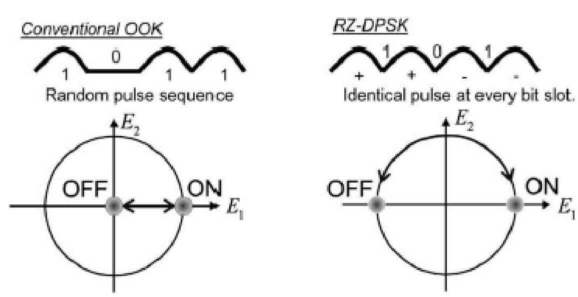
OOK V.S. DPSK[2]

MZM (Intensity) Transfer function

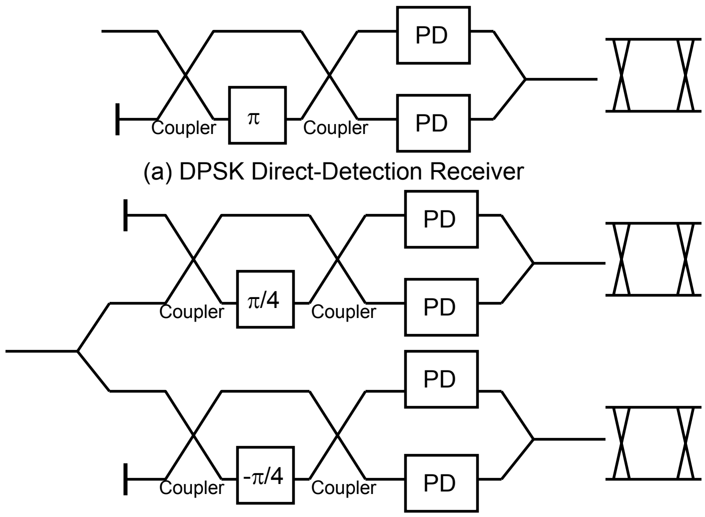


NRZ-OOK Driving

Intensity of DPSK signal



Direct-Detection DPSK Receiver[3]



(b) DQPSK Direct-Detection Receiver

Why D(Q)PSK Signals

- Can use direct-detection less expensive than coherent detection.
- Using direct-detection balance receiver has 3dB sensitivity gain.
- Tolerance to the fiber nonlinearity.
- DQPSK signal Improves spectral efficiency.

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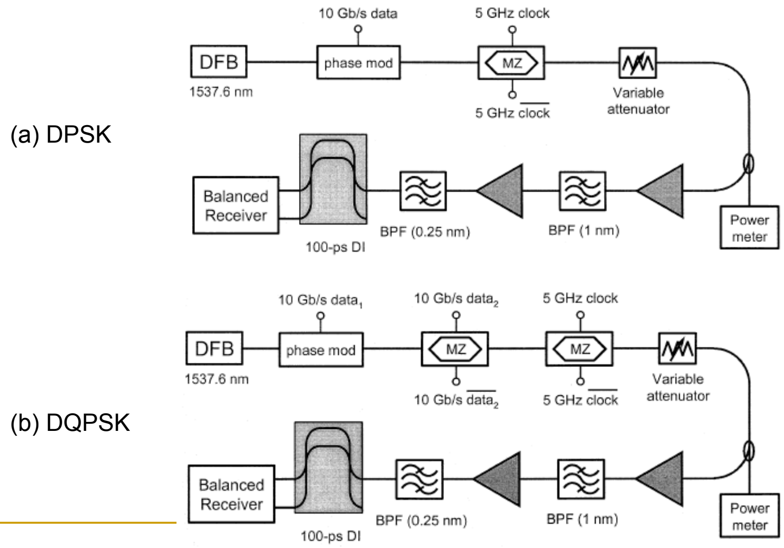
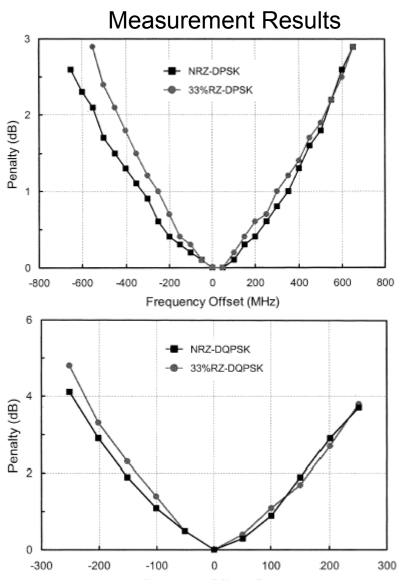
Source of Phase Error[4,5]

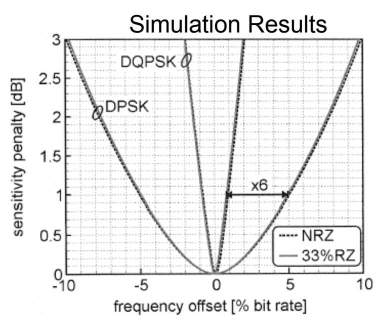
- Wavelength drift of the optical source
- Polarization rotation of the signal (if MZI has residual polarization-dependent path-length difference.
- Laser phase noise (carrier phase jitter)

Experiment Setup[4]



Penalty of Laser Frequency Offset[3]





Sensitivity Penalty	DPSK		DQPSK	
1 dB	± 3%	±1200 MHz	± 0.5%	±200 MHz
2 dB	± 5%	±2000 MHz	± 0.8%	±300 MHz

Analytical Solution (DPSK)[5]

- At the output of balance receiver
- $$s(t) = \left|E(t) + e^{j\theta_e} E(t-T)\right|^2 - \left|E(t) - e^{j\theta_e} E(t-T)\right|^2$$
- From digital communication textbook [6, p311], the error probability of correlated binary signals is

$$p_e = Q(a,b) - \frac{1}{2} e^{-(a^2+b^2)/2} I_0(ab)$$

$$a = \sqrt{\frac{\rho_s}{2}\left(1 - \sqrt{1-|\rho|^2}\right)} \qquad b = \sqrt{\frac{\rho_s}{2}\left(1 + \sqrt{1-|\rho|^2}\right)}$$

- $Q(a,b)$: Macum Q function.
- I_0(x): 0-th order modified Bessel function of first kind.

- If the MZI mismatch to the signal with $\theta_e = 2\pi\Delta f$ T, apply [6, Eq 4.2-44] then

$$\rho = \frac{\Re\left\{\left(1+e^{j\theta_e}\right)\left(1+e^{-j\theta_e}\right)^*\right\}}{\left|1+e^{j\theta_e}\right|^2} = \sin\theta_e$$

Series Expansion for BER of DPSK

- From any standard communication textbook

$$P_e = \frac{1}{2} e^{-\rho_s} \stackrel{?}{=} \frac{1}{2} - \frac{\rho_s e^{-\rho_s}}{2} \sum_{k=0}^{\infty} \frac{(-1)^k}{2k+1} \left[I_k\left(\frac{\rho_s}{2}\right) + I_{k+1}\left(\frac{\rho_s}{2}\right)\right]^2$$

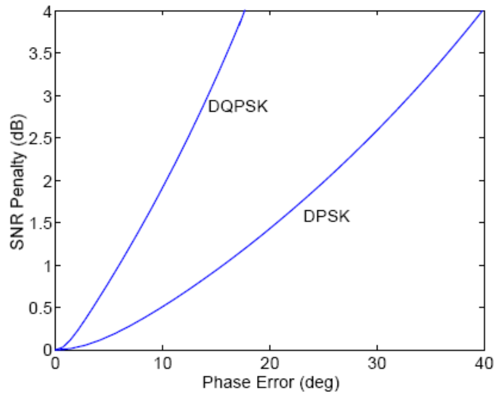
- With phase error θ_e the error performance in series expansion is

$$p_e = \frac{1}{2} - \frac{\rho_s e^{-\rho_s}}{2} \sum_{k=0}^{\infty} \frac{(-1)^k}{2k+1} \left[I_k\left(\frac{\rho_s}{2}\right) + I_{k+1}\left(\frac{\rho_s}{2}\right)\right]^2 \times \cos[(2k+1)\theta_e]$$

- Similarly, BER of DQPSK can be derived analytical via series expansion techniques.
- Series expansion method is powerful when noise is independent to amplitude noise. (weak correlation gives good approximation), e.g. if laser phase noise is zero-mean Gaussian distributed with variance of $\sigma_{\phi_e}^2$.

$$p_e = \frac{1}{2} - \frac{\rho_s e^{-\rho_s}}{2} \sum_{k=0}^{\infty} \frac{(-1)^k}{2k+1} \left[I_k\left(\frac{\rho_s}{2}\right) + I_{k+1}\left(\frac{\rho_s}{2}\right)\right]^2 \times \exp\left[-\frac{(2k+1)^2}{2}\sigma_{\phi_e}^2\right]$$

SNR Penalty v.s. Phase Error



Note: The baseline is the SNR requirement BER of DPSK signal at 10^{-9}.

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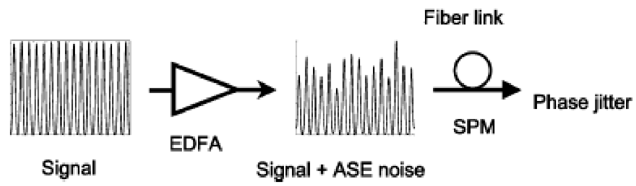
What is Self-Phase Modulation (SPM)



- Self phase modulation is a process occurred in a third-order nonlinear medium (optical Kerr effect).
- The phase in optical pulse is changed due to the change in the refractive index caused by the pulse.
- Intensity of optical signal plus noise induced phase perturbation.
- SPM causes positive chirp.

SPM Induced Nonlinear Phase Noise(1)

- At high optical power, the refraction index of silica must include the nonlinear contribution
- Refractive index has an intensity-dependent component.
- Causes an induced phase shift that is proportional to the intensity of pulse.
- Different part of the pulse undergo different phase shifts →pulse chirping →enhance pulse broadening of Chromatic Dispersion.
- More pronounce in system using high transmitted powers or high-bit-rate (>10Gbps)
- SPM + dispersion are what matters (limitations).

$$n_r' = n_{r0} + \bar{n}_2 \left(P / A_{eff} \right)$$

Effective Core Area

Refraction index at small power

Nonlinear-index coefficient

SPM Induced Nonlinear Phase Noise(2)

- Consider signal in electric field

$$S(z,t) = E\cos\left(\omega_0 t - \beta_0 z\right), \quad \beta = \frac{\omega n}{c} = \beta_0 + \left(\frac{\omega_0 \bar{n}_2}{A_{\text{eff}} c}\right) P$$

γ

- In each fiber span, overall nonlinear phase shift is

$$\Phi_{\text{NL}} = \int_0^L \gamma P(z)\, \text{dz} = \gamma L_{\text{eff}} P$$

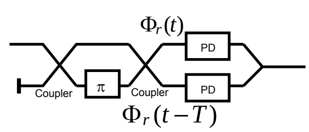
- With large fiber spans and noise

$$\Phi_{\text{NL}} = \frac{\gamma L_{\text{eff}}}{L} \int_0^{L_T} \left|E + n(z)\right|^2 \, \text{dz}$$

BER Approximation

- First, find characteristic function of different phase (balance receiver)

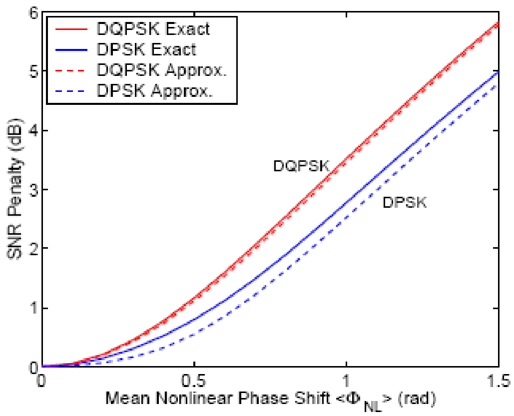
$$\Delta\Phi_r = \Phi_r(t) - \Phi_r(t-T)$$



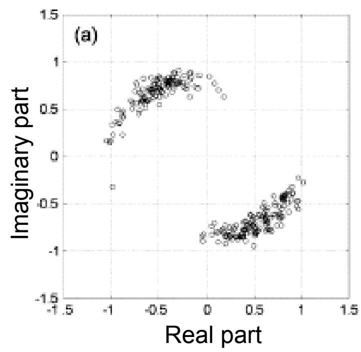
- Given a characteristic function $\Psi_{\Phi_r}(\nu)$ the error probability in series form

$$p_e = \frac{1}{2} - \frac{2}{\pi} \sum_{k=0}^{+\infty} \frac{(-1)^k}{2k+1} |\Psi_{\Phi_r}(2k+1)|^2$$

SNR Penalty v.s. Nonlinear Phase Noise



Note: The baseline is the SNR requirement BER of DPSK signal without SPM at 10^{-9}.



Phasor diagram of E-field

Conclusion

- D(Q)PSK with balance receiver has better receiver sensitivity and tolerance to fiber nonlinearity.
- SPM + Chromatic Dispersion results in performance limitations for optical fiber transmission systems.
- DQPSK is about 6 times more sensitive to frequency offsets than DPSK systems at the same bit rate.
- Series expansion is powerful when other noise source is independent to amplifier noise.
- For D(Q)PSK long-haul transmission systems nonlinear phase need to be compensation.

Reference

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